

# Designing Better Scaffolding in Teaching Complex Systems with Graphical Simulations

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## ABSTRACT

### Designing Better Scaffolding in Teaching Complex Systems with Graphical Simulations

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Complex systems are an important topic in science education today, but they are usually difficult for secondary-level students to learn. Although graphic simulations have many advantages in teaching complex systems, scaffolding is a critical factor for effective learning. This dissertation study was conducted around two complementary research questions on scaffolding: (1) How can we chunk and sequence learning activities in teaching complex systems? (2) How can we help students make connections among system levels across learning activities (level bridging)? With a sample of 123 seventh-graders, this study employed a 3x2 experimental design that factored *sequencing methods* (independent variable 1; three levels) with *level-bridging scaffolding* (independent variable 2; two levels) and compared the effectiveness of each combination. The study measured two dependent variables: (1) *knowledge integration* (i.e., integrating and connecting content-specific normative concepts and providing coherent scientific explanations); (2) *understanding of the deep causal structure* (i.e., being able to grasp and transfer the causal knowledge of a complex system).

The study used a computer-based simulation environment as the research platform to teach the ideal gas law as a system. The ideal gas law is an emergent chemical system that has three levels: (1) *experiential macro level* (EM)(e.g., an aerosol can explodes

when it is thrown into the fire); (2) *abstract macro level* (AM) (i.e., the relationships among temperature, pressure and volume); (3) *micro level* (Mi) (i.e., molecular activity). The *sequencing methods* of these levels was manipulated by changing the order in which they were delivered with three possibilities: (1) *EM-AM-Mi*; (2) *Mi-AM-EM* ; (3) *AM-Mi-EM*. The *level-bridging scaffolding* variable was manipulated on two aspects: (1) inserting inter-level questions among learning activities; (2) two simulations dynamically linked in the final learning activity.

Addressing the first research question, the Experiential macro-Abstract macro-Micro (*EM-AM-Mi*) sequencing method, following the “concrete to abstract” principle, produced better knowledge integration while the Micro-Abstract macro-Experiential macro (*Mi-AM-EM*) sequencing method, congruent with the causal direction of the emergent system, produced better understanding of the deep causal structure only when level-bridging scaffolding was provided. The Abstract macro-Micro-Experiential macro (*AM-Mi-EM*) sequencing method produced worse performance in general, because it did not follow the “concrete to abstract” principle, nor did it align with the causal structure of the emergent system. As to the second research question, the results showed that level-bridging scaffolding was important for both knowledge integration and understanding of the causal structure in learning the ideal gas law system.

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## **DEDICATION**

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## **CHAPTER I.**

### **INTRODUCTION**

#### **Section 1. Overview of the Research Topic**

It is usually difficult for secondary-level science students to learn complex systems. Complex systems have multiple “levels”; for example, a student can understand gas properties at their macro level (e.g., an aerosol can filled with gas will explode when the temperature is too high), but can also look at this phenomenon at its micro level (e.g., gas molecules move faster and bounce off the container walls more frequently). Yet it is often difficult for students to understand that something happening at a macro level is caused by something happening at a micro level—something that behaves very differently from what they see.

There are two major instructional goals in teaching a complex system. First, we as teachers want students to effectively integrate system content knowledge. Second, we want them to understand the deep causal structure of the system. Graphical simulations have many advantages for teaching complex systems. For example, simulations can create a visual depiction of the otherwise invisible or implicit system dynamics, and are able to clearly show system levels with multiple representations. However, we cannot merely rely on the learning environment as a tool for effective teaching. Scaffolding is a critical factor we need to address in instructional design when teaching complex systems.

This study focuses on two complementary questions regarding scaffolding in teaching complex systems: 1. How can we chunk and sequence the learning activities?

And, 2. How can we help students make connections among system levels across different learning activities?

### **Sequencing Methods in Teaching Complex Systems**

There has been much debate on how to sequence learning activities while teaching complex systems. Some studies assert that it is better to utilize a “top-down” sequencing method, starting with a concrete experiential phenomenon, breaking it into parts, and then explaining how the “whole” is caused by the “parts.” For example, at the beginning of a lesson on the respiratory system, students can start by reasoning about some experiential phenomena such as “one breathes faster when exercising.” Then, asking additional “why” and “how” questions, students can further learn how different organs and their substructures work together to help us breathe (Liu & Hmelo-Silver, 2009). But other studies contend that it is better to take a “bottom-up” sequencing method, starting with the micro-level dynamics. With the “bottom-up” sequencing method, students can experience how these simple, small effects cause something dramatic at a macro level. For example, during instruction on electricity concepts, it is usually easier for students to start from the “electrons” level, and then to experience how these micro-level electrons cause the macro-level electric current and voltage phenomena.

Why do these studies yield different results? One reason is that the two methods can serve different purposes. Research shows that the “top-down” sequencing method starting from a concrete macro-level phenomenon is often used to teach biological and life systems with many levels and ascending complexity from a macro to a micro level.

This sequencing method not only grounds abstract system concepts in everyday experience, but also provides a conceptual structure for knowledge integration. The “bottom-up” sequencing method, by contrast, is often used to teach systems with abstract causal structures, such as physics and chemistry. This sequencing method is effective for such topics because students can experience the process of how micro-level dynamics cause macro-level patterns to emerge (or the deep causal structure of the system).

The traditional approach to teaching complex systems often starts with abstract macro-level concepts, such as “energy” and “magnetic field.” It then goes on to the micro level such as “electrons” and “molecules.” After students learn the formal representations, they then apply the theories to solve everyday science problems. However, the technique does not support conceptual understanding. In this project, the three sequencing methods introduced above were compared to provide some answers to the first research question: How can we chunk and sequence the learning activities while teaching complex systems?

### **Level-Bridging Scaffolding in Teaching Complex Systems**

As students often learn different system levels sequentially in different learning activities, we have to help them make connections. There are different strategies for doing that. For example, two simulations representing two system levels can be linked together and then change simultaneously (software-realized scaffolding). We can also explicitly ask inter-level questions; students are then guided to explain how something that happens at one level can be explained by another level. For example, after students

learn about electrons' behaviors and "voltage" phenomena, we can explicitly ask them to explain how the micro-level electrons could cause "voltage" to emerge. In this way, students are more likely to bridge these system levels through active self-explanation. This so-called level-bridging scaffolding is another variable studied in this project.

## **Section 2. Overview of Dissertation**

Chapter 2 is a literature review. The review centers on a few major questions: 1. Why are complex systems difficult to learn? How can we analyze the learning difficulties students face on different dimensions? 2. What are the advantages of graphical simulations in addressing these learning difficulties? And, 3. How can we design better scaffolding for teaching complex systems? To address the third question, the mechanisms of different sequencing methods (why one sequencing method is effective or ineffective in a certain context) and level-bridging scaffolding are reviewed.

Based on the conceptual framework from chapter 2, chapter 3 delineates the variables and hypotheses. The two variables (sequencing methods and level-bridging scaffolding) need to be explained in a concrete context; and in chapter 4, the learning topic (the "ideal gas law" system) and the instrument (a simulation-based environment) are described. The study methodology is extensively described and discussed in chapter 5. The study results are presented in chapter 6, and the ways in which the data support the hypotheses are discussed. In chapter 7, the results are further discussed around the conceptual framework, and the pedagogical implications are addressed, as well as the limitations of this study and future research directions.



### **Section 3. Scholarly Significance**

Reasons for the major scholarly significance of this study include: 1) An argument for a multi-dimensional framework in analyzing difficulties in learning complex systems; 2) The study addresses the debate over sequencing methods in teaching complex systems; 3) The study shows the positive effects of level-bridging scaffolding in teaching complex systems; and 4) It provides implications for the effectiveness of instructional design with simulations in teaching complex systems.

## **CHAPTER II.**

### **LITERATURE REVIEW**

This chapter provides a review of the complex systems field and the related pedagogical issues. Section 1 discusses the nature of complex systems; following the first section, section 2 analyzes three major learning difficulties students often encounter during instruction. Graphical simulations are often applied in teaching complex systems, and section 3 discusses how the advantages of graphical simulations address the learning difficulties.

When teaching complex systems with graphical simulations, scaffolding is critical; indeed, this is the research topic of this dissertation project. The importance of scaffolding is discussed in section 4. Section 5 and 6 review the literature around the two complementary research questions regarding scaffolding: 1. How can we chunk and sequence learning activities while teaching complex systems? And, 2. How can we help students link different system levels across different learning activities? Overall, this chapter provides a conceptual framework for this dissertation project.

#### **Section 1. Nature of Complex Systems**

Complex systems are an important topic in science education today, but they are usually difficult for secondary-level students to learn (Jacobson & Wilensky, 2006). This section discusses the nature of complex systems, including how complex systems can be analyzed with a “levels” lens.

## **“Levels” in Complex Systems**

Complex systems have multiple “levels.” Thinking in terms of these levels gives students a fundamental ability to understand the scientific world (Wilensky & Resnick, 1999; Penner, 2000). For example, one can understand genetics phenomena from their macro levels; e.g., the skin color of a child depends on his or her parents. One may also, however, need to look at the micro-level dynamics, such as gene expression, from which the macro-level patterns emerge. To give another example, one can understand gas properties from its macro-level phenomena (e.g., if you throw an aerosol can into the fire, it will explode because of the high temperature). Yet to fully understand this phenomenon, one also needs to look at the micro-level gas molecular activity. All gas molecules move randomly following simple rules; when temperature increases, gas molecules will move at a higher speed and bounce off the walls more frequently, and the total gas pressure increases as an emergent function from the molecular activity. There are also many complex systems in the social science field. For example, socio-economic patterns, as macro levels, emerge from the behaviors and interactions of individuals and families at the micro level.

The notion of “levels” provides us with a powerful approach to understanding a variety of phenomena (Penner, 2000; Wilensky & Resnick, 1999). The three examples discussed above are from different scientific disciplines. You may see the value of emphasizing complex system concepts such as “levels” and “emergence” in many aspects of today’s science curriculum (Jacobson & Wilensky, 2006). There is a trend toward unifying central themes of complex systems from multidisciplinary fields (Bar-Yam, 1997), and teaching complex system concepts such as “levels” and “emergence” at the

secondary level can have great advantages for students' future learning (Jacobon & Wilensky, 2006).

It has been found, though, that students often fail to go beyond the macro level in learning complex science systems. For example, when learning about the human body as a system, high school students tend to focus on the basic structure of the macro-level elements and fail to integrate micro-level knowledge of system processes (Assaraf et al., 2013). In a similar example, even college students have many incorrect ideas about the micro-level dynamics of ideal gas law phenomena (Kautz et al., 2005b).

### **Another Dimension in Analyzing “Levels”: Experiential vs. Abstract**

System levels can be analyzed in several different dimensions: macro and micro, and experiential and abstract (Dori & Hameiri, 2003; Russell et al., 1997). For example, one can understand the ideal gas law system from multiple perspectives: experiential macro-level (e.g., a balloon pops when you push against it); abstract macro-level (abstract pressure-volume relationship); micro-level (gas molecular activity); and also as a symbolic mathematical equation. To fully understand this chemical system, one needs to be able to translate among these representations (Levy & Wilensky, 2009).

Instructional design needs to address both the features of the learning topic and student characteristics (Besson et al., 2010). Under this notion, when teaching complex systems, we not only need to have a “levels” lens to analyze the system, but also need to address questions such as, “Is this level of the system meaningful to the students?” and “How much everyday experience do students need in order to understand this system

level?” For example, in the teaching of many chemical and physics systems, macro-level concepts such as “energy” can be very abstract to students (Nordine et al., 2011). Kautz et al. (2005a) also find that even college students have difficulties understanding macro-level concepts of ideal gas laws (i.e., pressure, volume, and temperature). We as instructors need to ground abstract system levels in concrete experience to make them more accessible (Levy & Wilensky, 2009; Davis & Linn, 2005). For example, in teaching “magnetic field” to college students, Guisasola et al. (2009) find that introducing various everyday “magnetic field” phenomena facilitates learning.

## **Section 2. Difficulties in Learning Complex Systems**

In the previous section, the nature of complex systems was analyzed, so we now have a framework in which to ground our discussion of the learning difficulties involved. There are three major difficulties students often encounter in learning complex systems.

### **Difficulty 1: Knowledge Integration**

Knowledge integration is an important construct in science learning. It refers to students connecting scientific concepts and normative ideas, and providing coherent explanations to the scientific phenomena (Linn, 2006).

A system can be difficult to grasp when it has a large number of “levels,” and the dynamics (formation, operation, interactivity) at these many levels are also complex (Bar-yam, 1997). It’s difficult for students effectively connect new knowledge units to

their prior knowledge, mentally reorganize them and provide coherent explanations to many complex system phenomena. Many biological and natural systems bear this nature (e.g., Hmelo-Silver et al., 2007; Duncan & Reiser, 2007; Assaraf et al., 2013). For example, “when one runs he breathes faster” is a macro-level phenomenon of our respiratory system. Different organs work together systematically to make that happen. Each organ’s unique function (e.g., the function of lungs is air exchange) is realized by the complex interactions of its substructures at a lower level. At the micro level of the system, the dynamics of blood cells moving, O<sub>2</sub> and CO<sub>2</sub> molecules going across membranes, and chemical reactions are all happening simultaneously. As can be seen, the respiratory system has a “downward tree” structure with ascending complexity from macro to micro level (Assaraf et al., 2013). In order to understand how the respiratory system works, students need to integrate a large amount of system knowledge and also reorganize it internally to construct a coherent explanatory model.

It takes a good deal of effort to integrate system knowledge at multiple levels and construct a coherent explanatory model. Integrating and mentally reorganizing a large amount of system knowledge units may impose a heavy cognitive load. From the perspective of knowledge integration, learning needs to be chunked and sequenced to reduce this cognitive load (Pollock et al., 2002).

Students need a conceptual structure to effectively integrate system knowledge. The structure-behavior-function framework (SBF) has been proven as such an effective framework (Hmelo-Silver et al., 2007). “Structure” refers to the elements of a system; “behavior” refers to the mechanism of how the elements act and interact, leading to certain outcomes; and “function” refers to the roles of the elements or the outcomes

caused by the elements' behaviors and interactivity. For example, the respiratory system is composed of airways (the nose, windpipe, bronchus, etc.), respiratory muscles, lungs, and other elements. This is structural knowledge. Lungs are for air exchange, and airways make sure that clean and moisturized air successfully comes into the lungs. This is functional knowledge. Functions of a structure can be realized by its lower-level elements' actions; this is defined as behavior knowledge (e.g., O<sub>2</sub> comes across the membrane). Learning gas properties requires students to understand gas molecules as the basic components of gas (structural knowledge); lower-level mechanics such as random movement of gas molecules, change of speed, and collision (behavior knowledge); and also to understand how these behaviors cause the emergent macro-level gas properties such as pressure (functional knowledge). Organizing system information around system functions (at the macro level) provides a good conceptual structure for information integration (Liu & Hmelo-Silver, 2009), in other words, first show that something happens at a macro level (functional), and then explain how and why it happens (lower-level elements' behaviors and interactivity).

## **Difficulty 2: Learning the Deep Causal Structure of Complex Systems**

Integrating scientific conceptions and learning the causal structures are two forms of deep learning. Although they are not mutually exclusive, the former emphasizes the more domain specific content (Lee et al., 2011) and later focuses more on the abstract relational knowledge that is more transferrable across contexts (Grotzer, 2003).

“Emergence” is a kind of deep causal structure in complex systems. This emergent view of levels is very difficult to learn. According to Wilensky & Resnick (1999), there are three ways to think about levels. One is to take an “organization-chart view” approach with a hierarchy of control; e.g., a company is a management system with a hierarchy of control. Another is to take a “container view” or “whole-part view,” in which a higher-level whole is simply added up to by its lower-level parts with no interactions among the lower-level elements; e.g., this dissertation is composed of chapters, and a furniture is assembled by its parts. Finally, one can take an “emergent view,” in which a higher level arises from the interactivity of its lower-level entities, and a higher level is more than the added-up of the entities (Jacobson, 2001). The “emergent view” of levels is the one that we deal with in learning complex systems.

The deep causal structures of complex systems are often implicit or even seem counterintuitive to students. Novice students often focus on the static structure of a complex system, but not on the implicit processes and causal relations (Jacobson, 2001; Assaraf et al., 2013). Chi et al. (2012) analyze the reasons why the causal structures in emergent systems are so difficult to learn. Students have very robust misconceptions about complex systems (Chi, 2005). For example, students tend to believe causality is always in a linear and sequential manner; i.e., A causes B to happen, and B then causes C to happen. It is counterintuitive for students to look at a system with the “levels” lens and understand how dynamics of multiple levels are aligned and run simultaneously. Students tend to believe instead that in a system, some higher-level power controls the behaviors of the elements (which is called a “central control” schema). It’s very counterintuitive to believe that all micro-level elements behave randomly following



simple rules from which a higher-level pattern emerges (Jacobson, 2001; Chi, 2005; Chi et al., 2012).

The deep causal structure of an emergent system is also inherently difficult for students to construct and transfer. For example, although one study found that students were able to think and reason about some complex system concepts after learning with the StarLogo simulations (an agent-based modeling tool), concepts such as “emergence” were not successfully transferred to new problems (Wilensky & Resnick, 1995). Chi et al. (2012) used contrast cases to help students learn “levels” and “emergence”; this approach was proven effective for learning system content knowledge, but students did not successfully grasp complex system concepts such as “emergence.”

Reasoning about the causal structures may have positive effects on transfer performance (Grotzer, 2003). Students construct mental models of the causal structure in a learning context, and map the structural analog in solving new problems (Gentner, 1983; Monaghan & Clement, 1999). Causality induction is influenced by the temporal difference among events (Hagmayer & Waldmann, 2002). Thus it is reasonable to expect that a sequencing method aligned with the causal structure of a complex system will lead to better transfer performance.

There are two principles that we as educators may follow when teaching “levels” and “emergence” to students. One way is to let them experience the system dynamics and cross-level processes (Levy & Wilensky, 2009). For example, in a simulation-based environment, students can observe the dynamics of ink and water molecules (micro-level entities), manipulate the parameters, and observe how the diffusion phenomenon emerges. The other is to provide explicit scaffolding to help students reason the

underlying causal structure in a complex system (Jacobson & Wilensky, 2006). For example, when teaching diffusion as an emergent system, the micro-level dynamics simulation and the macro-level phenomena simulation can be displayed together and dynamically linked, which allows students to make connections (Chi, 2012). Additionally, scaffolding questions can guide students to explain the micro-macro relationship (Stieff et al., 2013).

### **Difficulty 3. The Abstractness of System Levels**

Many studies have found that the micro-level dynamics of a complex system are often abstract, and that students often ignore the microscopic perspective in analyzing system phenomena (e.g. Stieff et al., 2013; Assaraf et al., 2013; Kautz et al., 2005b). Systems with abstract or invisible micro-level dynamics often cause students to experience levels confusion (Stieff et al., 2013). For example, it tends to be difficult for students to visualize abstract micro-level elements such as electrons and molecules, and it takes effort for them to derive the linkages between a macro and a micro level (Frederiksen et al., 1999). To help students tackle levels confusion, computer simulations and modeling tools can be used to make the micro-level dynamics visually salient (e.g. Wilensky & Stroup, 2002).

The macro level of a complex system, when represented formally, can also be very abstract. For example, even college students have difficulty correctly understanding “gas pressure” as a macro-level gas law concept (Kautz et al., 2005a). Similarly, “magnetic field” as a macro-level concept, if not grounded in everyday experience, is

also very abstract to college students (Guisasola et al., 2009). Finally, many science concepts such as “energy” are macro-level concepts, but appear quite abstract (Nordine et al., 2011). There are two approaches that instructors can take in tackling an abstract macro-level concept. One is to ground it in everyday experience (e.g., Guisasola et al., 2009; Nordine et al., 2011). The other is to let students experience and figure out how an abstract macro level arises from micro-level dynamics (Levy & Wilensky, 2009). These two approaches have been shown to help students conceptually understand abstract macro-level concepts.

### **Analyzing a Complex System From Multiple Perspectives**

Although the three learning difficulties always coexist in complex systems, one may define the complexity more than another in a certain context. In learning many biological and natural systems, it is often difficult to integrate and organize a large number of system knowledge units (e.g., Duncan & Reiser, 2007; Hmelo-Silver & Pfeffer, 2004). For example, the human circulatory system has a downward tree-shaped structure with a large number of different elements, and varied element interactivity and behavior-functional processes across many levels. We may find information integration is a learning obstacle that students need to conquer before constructing a coherent explanatory model and an emergent causal model (if there is emergence involved).

Abstract causal structure can be seen in many complex chemical and physical systems. The amount of content knowledge may be small, but certain levels of these systems and cross-level causal processes could be implicit, abstract, and counter-

intuitive, with students often focusing on the macro-level phenomena and experiencing levels confusion (Stieff et al., 2013). For example, although electrons are the only micro-level entities we analyze in learning the electrical circuit system, and although electrons follow simple rules (there is little in the way of detailed structural and behavioral knowledge), it tends to be difficult to visualize “electrons’ actions” and “voltage” as emergent phenomena arising from electrons’ behaviors. To cite another example, it is typically difficult for students to see “lighting up a match” as a phenomenon emergent from chemical reactions at the molecular level (Stieff et al., 2013). Similarly, students also tend to find it challenging to understand “emergence” in various everyday phenomena such as the formation of a traffic jam or birds flocking together. One reason is that the “levels” are implicit in these systems, and the linkages among levels are not only implicit, but also counterintuitive (Jacobson, 2001).

Letting students experience the concepts of “levels” and “emergence” is an important principle in teaching emergent systems (Jacobson & Wilensky, 2006). To tackle this learning difficulty, instructors often use computer simulations to enable the visualization of abstract micro levels and emergent causal processes. The perceptual experience of system dynamics is very important in dealing with abstract micro-level dynamics (Goldstone & Wilensky, 2008). Agent-based modeling and visualizing tools can create such visual acuity of levels and emergence (e.g. Levy & Wilensky, 2006). A popular approach in these simulation-based environments is to let students manipulate the behaviors of micro-level elements and observe how a macro-level pattern emerges. For example, Wilensky and his colleagues developed the StarLogo environment, an agent-based modeling tool that has proven effective in teaching complex system concepts such

as emergence (Wilensky & Resnick, 1999). NetLogo is a similar simulation-based environment developed for the same purposes (Tissue & Wilensky, 2004). There is also evidence demonstrating that agent-based modeling simulations have positive effects on transferring complex system knowledge (Goldstone & Wilensky, 2008).

Multiple representations are often designed to help students visualize the dynamics of different system levels, and it is important for students to observe and derive, if possible, the linkages among the system levels (Frederiksen et al., 1999). For example, a simulation-based environment represents the macro-level phenomenon “ink diffusion” and its micro-level molecular dynamics at the same time. Students can be explicitly asked to make connections between the micro and macro levels (Chi et al., 2012).

### **Section 3. Learning Complex Systems with Graphical Simulations**

Simulation-based environments have many advantages in teaching complex systems including. First, they can help students to visualize abstract system dynamics. Second, they can represent multiple system levels through multiple representations. Finally, they can enable effective inquiry-based learning.

#### **Visualizing Abstract and Invisible System Dynamics**

Graphical simulations can vividly represent the otherwise invisible micro-level dynamics of a system (Wilensky & Resnick, 1999; Stieff, 2011). It becomes easy for

students to observe, for example, the molecular activities of a chemical system through a graphical simulation. Understanding a system involves constructing a mental perceptual simulation for information retrieval and reasoning (Black, 2010), and perceptual experience is very important for mental model construction in learning science systems (Barsalou, 2008). Some studies show that it is easier for students to conduct self-explanation when learning graphics, as compared with text (e.g., Ainsworth & Loizou, 2003). A multimodal perceptual experience through simulation-based environments also helps students to learn abstract system knowledge. For example, a graphical simulation controlled by hand movement was proven beneficial for middle school students attempting to learn the abstract relational structure of the “energy conservation” system (Chan & Black, 2006).

### **Representing “Levels” with Multiple Representations**

Simulation-based environments for teaching complex systems usually include multiple representations, which can provide complementary information, constrain interpretation of any singular representation, and support deeper understanding (Ainsworth, 2006). A concrete representation can be used to depict macro-level phenomena; for example, a bulb that lights up when one flips the switch is an experiential macro-level representation. The representation visualizes “electricity” and “voltage,” which are abstract macro-level concepts, and a representation visualizing how micro-level electrons behave and cause “voltage” can begin to emerge. Tasks can be designed to

enable students to actively connect and translate among multiple representations for deep learning (Bodemer et al., 2005; Ainsworth, 2006).

Multiple representations have significant advantages for teaching the “levels” notion and facilitating cross-level reasoning. For example, the SMV-chem program (Russell et al., 2000) is a learning environment with four representations teaching “equilibrium of heat” (an emergent chemical system). The four representations depict or describe different system levels: a realistic video of a lab experiment that demonstrates macro-level phenomena, a simulation that visualizes micro-level molecular activities, a dynamic graph, and a text-based explanation that represents the symbolic mathematical model of the system. Students can be guided to look at the system from multiple perspectives.

Multiple representations can also facilitate the construction of cross-level linkages in learning complex systems (Levy & Wilensky 2009). Techniques such as dynamically linking representations (i.e. representations that change simultaneously) could enable and enhance information integration and connection-making (van der Meji & de Jong, 2006). For example, in Chi et al. (2012)’s study, as a way to help students understand the concept of “emergence,” both macro-level and micro-level of “diffusion” are displayed, and change simultaneously in a simulation-based environment.

## **Inquiry-Based Learning in Simulation-Based Environments**

The visual and interactive nature of graphical simulations allows for the implementation of effective inquiry-based learning. Simulations provide perceptual resources for effective self-explanation and inferences generation (Gordin et al., 1996). There are, however, some principles that we as instructors need to follow in designing simulations for elementary- and secondary-level students. For example, we must balance the level of visual complexity, making the important information salient, but also avoiding oversimplification (Kali & Linn, 2008). Simulations may not benefit learning compared to information-equivalent static graphics if they don't follow the congruence principle (Tversky & Morrison, 2002). We must make sure that the way students process the information is aligned with ideal learning trajectories.

Cognitive load (Sweller & Chandler, 1994) and limited working memory (Baddeley, 1992) have been studied extensively in the field of multimedia learning. Spatial-temporal contiguity have been proven effective in reducing split attention (Kalyuga et al., 1999), and using dynamic link (van der Meji & de Jong, 2006) can reduce the cognitive load in learning multiple dynamic representations. Relevant information should be grouped together so that students can select and encode them together, particularly in complex learning environments (Ginns, 2006).

The theories above informed the author in designing and developing the research instrument for this dissertation project: a simulation-based environment teaching the ideal gas law system. In chapter 4, this instrument will be further discussed. Another principle in designing simulation-based environment for inquiry-based learning; specifically, we need to scaffold learning for effective reflection and self-explanation (Linn, 2006). In the



next section, I will discuss scaffolding.

#### **Section 4. Scaffolding as a Critical Factor in Teaching Complex Systems**

Simulation-based environments may offload much mental effort in visualizing the system dynamics and making sense of the content (Stieff, 2011); however, the cognitive and metacognitive demands from learning process management can be overwhelming (Reiser, 2004). Students require scaffolding to make connections across multiple representations, especially when certain representations or the connections are abstract (Ainsworth, 2008; Frederiksen et al., 1999). Scaffolding must balance two opposite approaches from the perspective of cognitive load. On the one hand, learning needs to be well structured and sequenced to artificially reduce intrinsic cognitive load (Pollock et al., 2002); on the other hand, we need to encourage cross-representational translation, which imposes germane cognitive load for deep understanding (Bodemer et al., 2005). Cross-representational mapping and translating tasks have proven very effective in learning complex math and science topics (Ainsworth, 2008).

Although multiple representations may have great advantages for teaching complex systems, mere perceptual experience without proper instructional design is insufficient for effective learning (de Jong, 2005; Kirschner et al., 2006; Hmelo-Silver et al., 2007). It is very likely that instruction plans will fail if teachers simply assume that novice students are able to plan and manage the learning process, correctly distribute their mental effort, and integrate knowledge effectively in complex learning environments (Hmelo-Silver et al., 2007). The function of a learning environment is to

shape students' thinking and guide the learning progress in optimal directions (Reiser, 2004; Schnotz & Lowe, 2008). Technology-enhanced tools are a part of a broader task, and should be molded together with other learning materials and various forms of scaffolding based on the learning goals (Quitana et al., 2004).

Scaffolding in technology-enhanced learning environments deserves further research, as there are many questions about it that remain. For example, in Renkl's (2002) study, a computer-based learning program teaching probability was used as the instrument. Renkl found that instructional explanation as scaffolding had certain positive effects for people with low prior knowledge, but that in general, the effects were not very satisfying. Further studies are needed to explain why and how a scaffolding strategy is effective or ineffective in a certain context. Similarly, much empirical evidence supports the claim that the learning process needs to be structured and sequenced in complex learning. This is called procedural scaffolding (see review in Quitana et al, 2004). When students lack sufficient prior knowledge to deal with the learning environment effectively, procedural scaffolding is more important (Mayer, 2004; Kriz & Hegarty, 2007; Lowe, 2004).

Scaffolding theories and practices have many implications for the field of complex systems learning. Previous researchers, for example, have emphasized that scaffolding must be explicit in teaching complex systems (Jacobson & Wilensky, 2006; Jacobson, 2011). Scaffolded knowledge integration frameworks aptly guide the practices of teaching science inquiry (Linn, 1995; Linn, 2006; Hmelo-Silver et al., 2007). The principles of such a scaffolded knowledge integration framework include "make science

accessible,” “make thinking visible,” “encourage active and autonomous learning,” and “provide social support” (Linn, 2006).

Scaffolding can take different forms in technology-enhanced learning environments, but the major functions and mechanisms of different scaffolding strategies can be similar (Quitana et al., 2004). There are two important mechanisms of scaffolding in facilitating complex learning. One is to structure and sequence the learning tasks for progress management; the other is to “problematize” the learning process to encourage reflection, self-explanation, and conflict resolution (Reiser, 2004). To align with this framework when teaching complex systems, on the one hand, we need to properly chunk and sequence the learning activities to reduce cognitive load; on the other hand, we need to encourage students to actively make connections among system levels (Levy & Wilensky, 2009; Frederiksen et al., 1999). To that end, there are two complementary research questions in this dissertation project: 1. How to chunk and sequence learning activities in teaching complex systems? And 2. How to help students make connections among system levels across different learning activities? The following two sections review the literature around these two questions.

## **Section 5. How Can We Chunk and Sequence Learning Activities in Teaching Complex Systems?**

Students do not grasp complex systems during short sessions. Learning these complex systems requires students to go through steps of conceptual enrichment and conceptual changes (Assaraf & Orion, 2005; Mohan et al., 2009; Vosniadou & Brewer,

1992). We, as instructors, need to properly chunk and sequence the learning activities to reduce cognitive load, which facilitates conceptual enrichment and conceptual changes (Pollock et al., 2002).

As reviewed in section 2, there are three major difficulties to be tackled in learning complex systems. However, one learning difficulty may be more salient than another in a certain context or at a certain learning stage. In learning some biological systems with multiple levels and many system knowledge units, successful knowledge integration could be a more salient learning difficulty at an early stage. By contrast, in learning a chemical system such as ideal gas law, the implicit causal structure and abstract system concepts (e.g., gas pressure) could be a primary hurdle. Either macro-level or micro-level, or both levels, can be abstract in a complex system.

All these factors may have led to the contradictory findings surrounding the question of “how can we chunk and sequence learning activities in teaching complex systems.” However, there are some general principles we need to follow, such as “ground abstract system knowledge in experience,” to make science more accessible (Linn, 2006; Levy & Wilensky, 2009), “provide a conceptual structure to integrate and organize system information” (Liu & Hmelo-Silver, 2009), and “let students experience the implicit causal relations and processes in the system to support conceptual understanding” (Jacobson & Wilensky, 2006). The purpose of this section is to review different approaches to chunk and sequence learning activities (or sequencing methods) in teaching complex systems, and to explain why and how each method is effective or ineffective in a certain context.

## Levels in a Prototype Emergent System

To guide a clear experimental design, the levels of a prototype emergent system are defined including an experiential macro level, an abstract macro level and a micro level (see *Table 1*, p.27). An experiential macro level is an observable and concrete representation of the macro-level relationships. An abstract macro level is a formal representation of the macro-level relationships, which is structurally and functionally analogous to the experiential level. These two macro levels are emergent from micro-level dynamics. Many physics and chemical emergent systems have this structure. The micro level of a chemical or a physics system is always abstract; however, with the help of various visualizing tools such as graphical simulations, students are able to observe and analyze the micro-level dynamics which are otherwise invisible. Below are two examples to help readers understand the three levels of an emergent system.

### *Example 1*

In the electrical system, the experiential macro level represents observable phenomena such as a bulb light up in a circuit when one flips the switch. This level depicts the macro-level relationships in a concrete manner thus is accessible to the students. The abstract macro level is a formal representation of voltage, current and resistance relationships. This level is often difficult to understand. The micro level of the electrical system is the electrons' behaviors and interactivity. The electrons behave and interact following simple rules, from which voltage and current phenomena emerge.

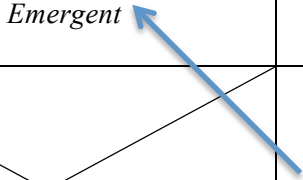

Emergence is the deep causal relations across levels, and is particularly difficult to grasp. In the electrical system, for example, electrons behave and interact simultaneously following simple rules. Voltage and current arise and change as a result of the micro-level electrons behaviors. The causal relationship is not linear or sequential, and there is no central control over the micro-level electrons.

### *Example 2*

Ideal gas law phenomena are another example. An aerosol can explodes when it is thrown into the fire. This is an experiential macro level. The abstract macro level of the system represents the abstract temperature-pressure relationship. The relational structure of the abstract macro level is analogous to and aligned with the experiential macro level. Gas molecular activity is the micro level. Emergence is involved in the ideal gas law system. All molecules move randomly and bump into the inner surface of the aerosol can. They follow simple rules (e.g., bump and change directions following simple mechanical rules; change speed in response to temperature change). At the abstract macro level, increased temperature causes pressure to increase is an emergent function caused by the molecular activity.

In the following sub-sections, three sequencing methods will be explained in the context of a prototype emergent system. After that, the advantages and disadvantages of each sequencing method will be reviewed.

Table 1. Levels in a Prototype Emergent System

	Experiential	Abstract
Macro	Observable macro-level phenomena	Formal representations of macro-level relationships
Micro		 Micro-level dynamics

### Sequencing Method 1: Experiential Macro-Abstract Macro-Micro (*EM-AM-Mi*)

The *EM-AM-Mi* sequencing method is a “top-down” approach starting from the experiential macro-level function of a system. This sequencing method follows the “from concrete to abstract” principle, and provides a desirable conceptual structure for knowledge integration.

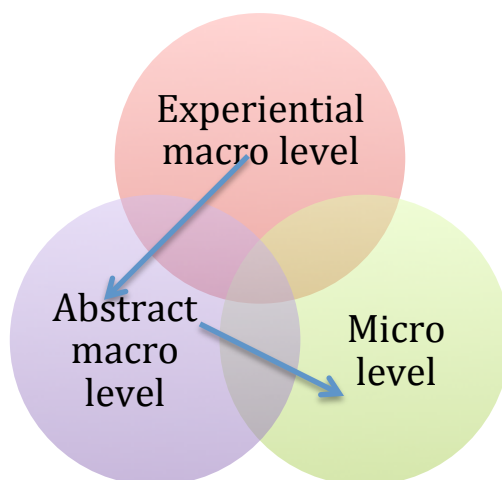


Figure 1. EM-AM-Mi Sequencing Method

### Sequencing Method 2: Micro-Abstract Macro-Experiential Macro (*Mi-AM-EM*)

This sequencing method takes a “bottom-up” approach starting from the micro-level dynamics. Students experience how small effects and simple interaction can cause something to emerge at a macro level. In other words, this sequencing method is aligned with the deep causal structure of an emergent system. In the ideal gas law system, for example, at the micro level, any single molecule moves randomly and bumps into the container walls. In response to a temperature increase, all the molecules move faster and bump into the walls more frequently with larger force. It is from the micro-level dynamics where increased pressure emerges as an effect. The increased pressure explains why an aerosol can explodes when it is thrown into the fire. You can find the congruency between the *Mi-AM-EM* sequencing method and the deep causal structure of an emergent system.



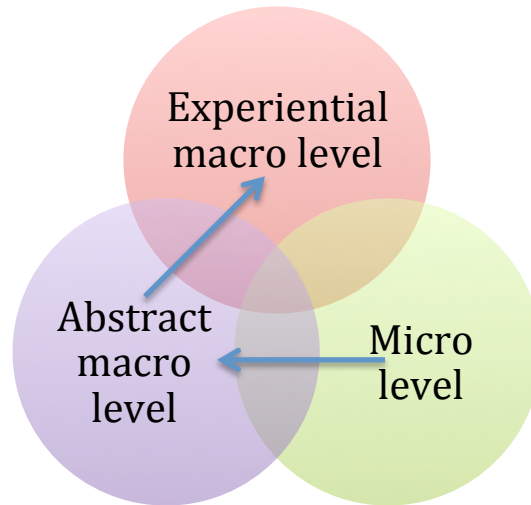


Figure 2. Mi-AM-EM Sequencing Method

### Sequencing Method 3: Abstract Macro-Micro-Experiential Macro (*AM-Mi-EM*)

This approach starts from an abstract macro level, then goes on to the micro-level dynamics. After learning the abstract system knowledge, students apply the knowledge to explain everyday science problems. This sequencing method does not follow “from concrete to abstract” knowledge integration principle, or align with the causal structure of an emergent system, thus it is hypothesized less effective than the other two sequencing methods. For example, if we start from Temperature-Pressure-Volume relationship when teaching the ideal gas law system, students don’t have enough prior knowledge to conceptually understand the concepts, thus effective knowledge integration is less likely to happen. Meanwhile, this “top-down” approach is incongruent with the emergent causal model.

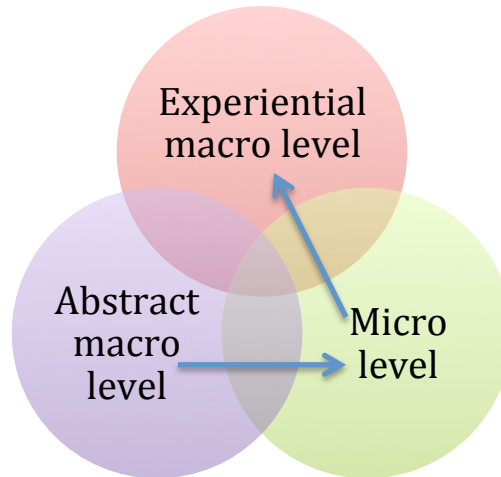


Figure 3. *AM-Mi-EM* Sequencing Method

In the next three sub-sections, advantages and disadvantages of the three sequencing methods will be comprehensively reviewed.

### **Advantages of the *EM-AM-Mi* Sequencing Method**

The *EM-AM-Mi* sequencing method (see *Figure 1*) is effective in tackling the first (Difficulty 1) and third difficulties (Difficulty 3). The first difficulty (Difficulty 1) is that it is difficult to integrate and mentally reorganize a large amount of system knowledge. The third (Difficulty 3) is that it is difficult to conceptually understand abstract system levels.

The *EM-AM-Mi* sequencing method provides a good conceptual structure for students to integrate and organize system knowledge. For example, in Liu & Hmelo-Silver's study (2009), they compared the "top-down" and "bottom-up" approaches in learning the respiratory system in a hypermedia learning environment. The "top-down"

approach, starting from the experiential macro-level function (“Why and how do we breathe?”) is more effective when compared to the bottom-up approach starting from complex micro-level system knowledge.

The *EM-AM-Mi* sequencing method is function-oriented. “How” and “why” questions about system functions help students to integrate detailed structural and behavioral knowledge (Liu & Hmelo-Silver, 2009). The macro level of this particular system is concrete and experiential, which facilitates knowledge integration. As can be seen in this type of biological system, a function is often realized through the interactivity of a large number of diverse lower-level substructures (in the case of the respiratory system, it has a downward tree-shaped structure). The function of the respiratory system (“breathing”) is more accessible to students as compared to the lower-level organs’ behaviors and the molecular-level mechanisms; it is also more intuitive and easier for the students to integrate information around the macro-level system function.

The “top-down” approach starting from an experiential macro-level “whole” makes science more accessible to students. “Making science accessible” as a knowledge integration guideline requires that concrete levels of a topic come before abstract ones (Linn, 2006); familiar representations before less-familiar ones (Frederiksen et al., 1999). For example, students are more familiar with the macro-level genetic phenomena of skin color than with the abstract micro-level elements of protein and DNA. The dynamics at the micro level could be much more complex or abstract than the macro-level phenomena. In those cases, the *EM-AM-Mi* sequencing method could be very effective.

When the mechanism and micro-level dynamics of a system are abstract, the *EM-AM-Mi* sequencing method allows students to relate abstract concepts to concrete

phenomena. Guisasola et al. (2009) demonstrate the effectiveness of this sequencing method in teaching abstract complex systems. In learning the “magnetic field” system, students who were taught to become familiar with various magnetic phenomena at the beginning produced better performance in further learning than their peers who learned the topic through the traditional approach (learn the microscopic theories of magnetic fields, and then apply the knowledge in solving magnetic field problems).

The *EM-AM-Mi* sequencing method also has advantages from the motivational perspective. It is more motivating to explain a science problem around concrete phenomena and probe into the underlying mechanism of real scientific problems, which is more of an inquiry-based method, than to utilize the traditional “equation-to-application” approach, in which one learns an equation and then uses it to solve a science problem. Guisasola et al. (2009) show that the *EM-AM-Mi* approach leads to higher motivation in students than if the “equation-to-application” approach is used in learning the magnetic field system.

### **Advantages of the *Mi-AM-EM* Sequencing Method**

The *Mi-AM-EM* sequencing method is useful in tackling the second (Difficulty 2) and third difficulties (Difficulty 3). The second difficulty (Difficulty 2) is that it is difficult to learn the implicit and abstract causal structures of a complex system. The third (Difficulty 3) is that it is difficult to conceptually understand abstract system levels. This sequencing method takes a “bottom-up” approach. The “bottom-up” approach has been applied in modeling complex systems in various disciplines, including chemistry (Levy &

Wilensky, 2006), ecology (Grimm, 1999), and economics (LeBaron, 2000). The sequencing method starts from micro-level dynamics before moving to macro-level patterns, and is particularly effective in teaching “emergence” (Wilensky & Stroup, 2002).

In learning many of the emergent systems discussed above, starting from the micro-level elements may be more accessible. The micro-level behaviors of these systems may be less complicated than those of some biological and natural systems; compared with the respiratory system, for example, there is less complicated structural formation and less diversified interactivity at the micro level, as well as fewer levels. From the perspective of knowledge integration, the difficulty is less overwhelming. Some macro-level concepts can also be more abstract than the micro-level concepts. For example, “gas pressure” as an emergent phenomenon is more abstract than “gas molecules.” Similarly, “electron movement” is much easier to understand than “voltage,” which is a macro-level concept.

Many emergent systems have abstract and implicit causal structures. This could prove to be more of a learning difficulty than knowledge integration. For example, it is easy for students to understand that there are a large number of vehicles in a traffic jam; within this, students will also find the behaviors of a single vehicle accessible. The most difficult part of learning these emergent systems is to understand the non-linear and decentralized causal processes, which is often counterintuitive and abstract (Jacobson, 2001; Chi, 2005). An emergent schema, that all micro-level elements behave following simple local rules and cause some macro-level patterns to arise, and that there is no

“magic” central higher-level power that controls the elements, is very difficult to construct (Chi, 2012).

The *Mi-AM-EM* sequencing method supports conceptual understanding of implicit causal structures, because it allows students to experience how micro-level behaviors cause macro-level phenomena. For example, in the Connected Chemistry Curriculum, developed at the Center for Connected Learning and Computer-Based Modeling at Northwestern University, the approach is to let students manipulate and articulate the micro-level behaviors of a complex system (e.g. how a single gas molecule collides with the walls), and then gradually expand to the emergent processes and phenomena. Researchers claimed that this “from-the-molecules-up” approach helped students to conceptually understand the implicit linkages between the micro and macro levels of gas phenomena (Levy & Resnick, 2009). Similarly, in learning some everyday complex systems such as traffic jams and bird flocking, taking a “bottom-up” approach, for example, by first manipulating the micro-level elements such as the local behaviors of a bird, is often most effective (Wilensky & Stroup, 2002). To bridge this “bottom-up” process, “a smaller scale mid-level” or an “aggregate level” can be used as a scaffold (Levy & Wilensky, 2008; Frederiksen et al., 1999). Students can gradually understand the process by which the simple interactivity of micro-level elements leads to emergent macro-level patterns.

The *Mi-AM-EM* sequencing method is more likely to represent an emergent-system problem, because it follows the causal process across system levels. How a problem is represented, as well as what kind of problem schemas or structural knowledge students have, may all predict success in problem-solving (Jonassen, 2000). Levy &

Wilensky (2004) compared “bottom-up” and “top-down” sequencing methods in learning complex systems such as equilibrium and stochasm, finding that the “top-down” approach produced a less robust understanding than the “bottom-up” approach. The congruency between the sequencing method and the system causal structure might help students construct a better mental model.

From the motivational perspective, the “bottom-up” approach could also create “surprise” moments triggering deep thinking. For example, after manipulating and observing the simple actions of vehicles, students participating in one study were very surprised to observe a traffic jam emerged and the patterns kept changing at the macro-level (Wilensky & Resnick, 1999).

### **Why is the *AM-Mi-EM* Sequencing Method Not Effective?**

The *AM-Mi-EM* sequencing method (see *Figure 3*) is not effective in tackling any of the three learning difficulties. This is because the approach does not effectively support conceptual understanding, as the abstract representation of a macro level is not very accessible to the students. For example, abstract scientific constructs such as “energy” and “pressure” are very abstract to secondary-level students when taught using this particular method (Nordine et al., 2011).

The *AM-Mi-EM* sequencing method also does not support information integration, as students lack an experience to relate to when they come across new system knowledge (Levy & Wilensky, 2009). “Making science accessible” as a knowledge integration guideline (Linn, 2006) specifies that concrete levels of a topic should come before

abstract ones, and familiar representations before the less familiar ones (Frederiksen et al., 1999). For example, students are more familiar with the higher-level function of the circulatory system and less familiar with the molecular-level mechanism. Further, the lower-level dynamics are more complex or abstract than those at the higher level, making a top-down pathway more intuitive. By contrast, when learning the magnetic field, the macro-level concepts are very abstract to students (e.g., textbooks usually use curved lines to represent magnetic field phenomena). In this case, starting with abstract macro-level knowledge does not support students relating the micro-level magnets' characteristics to the macro-level magnetic field (Guisasola et al., 2009).

To help students develop more integrated conceptions of science, we as instructors need to ground abstract science representations in concrete everyday phenomena. For example, in Nordine et al.'s (2011) study, researchers found that letting students experience “energy” in various everyday settings facilitated knowledge integration and conceptual understanding. This can also be aligned with “anchored instruction” (Bransford et al., 1990), which emphasizes the importance of situating formal, abstract knowledge in the physical world. The *AM-Mi-EM* sequencing method is not effective in teaching such abstract causal structures, because students do not experience the emergent causal process.

### **Summing up the Advantages and Disadvantages of the Three Sequencing Methods**

To sum up, for two key reasons, the *EM-AM-Mi* sequencing method is effective in helping students to tackle some of the learning difficulties that students experience during



instruction in complex systems. First, abstract system knowledge is grounded in everyday experience; second, the method provides a conceptual structure into which students can integrate detailed system knowledge. However, this sequencing method does not support constructing emergent causal structures, as students do not experience the process by which micro-level dynamics cause an emergent macro-level pattern.

The *Mi-AM-EM* sequencing method is also effective for two key reasons. First, students are able to experience how an abstract macro level emerges from micro-level dynamics, which supports conceptual understanding. Second, this sequencing method is aligned with the emergent causal processes across system levels; this congruency helps students to construct better mental models. However, this method does not provide a conceptual structure into which students can integrate detailed system knowledge. Finally, the *AM-Mi-EM* sequencing method is not effective, because it does not support conceptual understanding or knowledge integration; further, students are unable to experience the causal process from micro level to macro level.

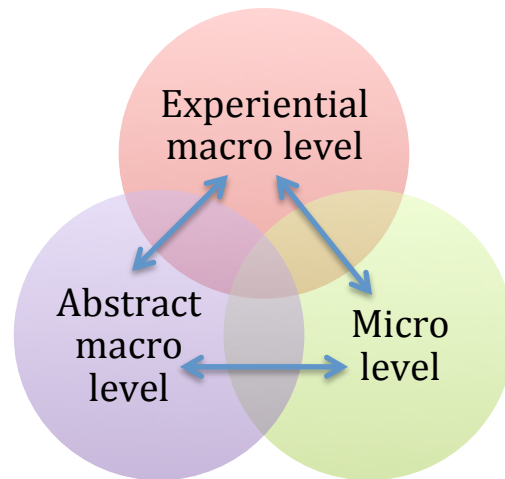
## **Section 6. How Can We Help Students Make Connections Among System Levels?**

It is critical to help students construct linkages among multiple levels when learning complex systems (Frederiksen et al., 1999; Levy & Wilensky, 2009). In this section, literature is reviewed to address two questions. First, why is level-bridging scaffolding important in learning complex systems? Second, how can instructors design level-bridging scaffolding?

## **The Importance of Level-Bridging Scaffolding**

When teaching complex science topics, instructors must contend with the fact that students often have fragmented knowledge of the subject matter and therefore fail to construct coherent explanatory models. Instructors must provide scaffolding for knowledge integration to occur (Linn, 2006). Liu & Hmelo-Silver (2009) found that asking “how” and “why” questions about system functions could help students integrate and internally organize detailed lower-level structural and behavior knowledge. This type of inter-level experience is also critical in helping students to learn about the deep causal structures of complex systems (Levy & Wilensky, 2009). Students must be able to understand how the macro level and micro level are aligned in order to be able to translate how the micro-level dynamics cause a certain macro-level pattern to emerge. To construct an “emergent schema” (Chi et al., 2012), students need to practice cross-level reasoning (Levy & Wilensky, 2008).

Following a constructivist view of learning, mapping structural and functional analogs of two representations allow people to generate new inferences, and enable conceptual changes (Genter & Markman, 1997; Limon, 2001; Vosniadou & Brewer, 1992). This aligns with the idea of “level bridging” in learning complex systems. Inter-level experience gained from translating across system levels is critical in constructing a good mental model (Levy & Wilensky, 2009)



*Figure 4. Inter-level Experience in Learning Complex Systems*

### **Designing Level-Bridging Scaffolding**

Different levels of a system can be depicted or described with multiple representations in a simulation-based environment. Mapping and translating across multiple representations facilitates deep understanding in students as they learn complex math and science topics (Bodemer, et al., 2005; Stieff, 2011; Ainsworth, 2008). Students need to be scaffolded, however, to make connections across multiple representations (Ainsworth, 2008; Frederiksen et al., 1999). “Dynamically linking the representations” is one form of software-realized scaffolding (van der Meji & de Jong, 2006). For example, when students observe and analyze the micro-level molecules’ behaviors and macro-level diffusion phenomena simultaneously, they are more likely to actively make connections between these two levels (Chi et al., 2012).

Simulation-based environments may offload much mental effort in bridging system levels; however, cognitive and metacognitive demand in this process can still be overwhelming. Instructional design and scaffolding is critical (Hmelo-Silver & Azevedo, 2006). Support is often needed to facilitate level bridging (Clement, 1993). When students observe the micro level and macro level of a complex system, they may have insufficient prior knowledge to interpret their observation or make connections.

Inter-level questions explicitly asking about the cross-level relations and processes can scaffold level bridging. First, inter-level questions support information integration (Cerdan & Vidal-Abarca, 2008). “Why” and “how” questions asking students to explain how a macro-level function is realized by micro-level dynamics could generate better knowledge integration (Liu & Hmelo-Silver, 2009). Second, inter-level questions can trigger causal explanations, thus facilitates better mental model construction. Causal mechanistic explanations facilitate mental visualization of system dynamics, which is an important cognitive mechanism in mental model construction (Kaplan & Black, 2003; Duncan & Reiser, 2007).

To sum up, level-bridging scaffolding needs to be explicit. There are two general approaches to support level bridging: 1. Software-realized scaffolding such as “linking multiple representations”; 2. External scaffolding such as inter-level questions to encourage cross-level reasoning.

## Section 7. Summary of the Conceptual Framework

Complex systems are an important topic in today's science education. Complex systems have multiple "levels". It's difficult for students to analyze a complex system with the lens of "levels" especially when the system levels are very abstract. There are three major learning difficulties we need to address in teaching and learning complex systems: 1. Integrate a large amount of system knowledge at multiple system levels 2. Understand the deep causal structure in a complex system 3. Conceptually understand abstract system concepts.

Graphical simulations have many advantages in teaching complex systems including visualizing the abstract system dynamics, represent multiple system levels, and facilitate cross-level reasoning. Regardless of those advantages, scaffolding is critical in learning complex systems.

There are two complementary questions regarding scaffolding to be addressed: 1. How can we chunk and sequence learning activities in teaching complex systems? 2. How can we help students make connections among system levels across learning activities?

This dissertation project was conducted to address the two questions above. Based on the literature review, the *EM-AM-Mi* sequencing method is hypothesized to facilitate knowledge integration; and the *Mi-AM-EM* sequencing method is hypothesized to facilitate understanding of the deep causal structure of an emergent system. The *AM-Mi-EM* sequencing method is not effective because it does not support conceptual understanding, nor properly represent the emergent causal process.

As to the second research question, level-bridging scaffolding is an effective strategy to help students construct linkages among system levels, thus facilitate knowledge integration and understanding of the deep causal structure of the system.

The literature reviewed in this chapter serves as the conceptual framework for this dissertation project. The hypotheses based on this conceptual framework are discussed in the next chapter.

Ideal gas law is an emergent complex system. This topic is in the secondary-level science curriculum. A simulation-based environment teaching the ideal gas law system was developed and used as the research instrument for this study. Chapter 4 analyzes this complex system from multiple perspectives and describes the simulation-based learning environment.

## CHAPTER III.

### RESEARCH QUESTIONS & HYPOTHESES

This dissertation project is built upon two complementary research questions on scaffolding: 1. How can we chunk and sequence learning activities in teaching complex systems? 2. How can we help students link different system levels across different learning activities? The author tested two variables, sequencing methods and level-bridging scaffolding, to address these questions.

#### Section 1. Independent Variables

##### Sequencing Methods

Three sequencing methods were compared in this study: *EM-AM-Mi*, *Mi-AM-EM* and *AM-Mi-EM* (See Figures 1, 2, and 3 in chapter 2). In order to manipulate the variable, the author changed the delivery order of the system levels.

##### Level-Bridging Scaffolding

Level-bridging scaffolding was compared to the control condition of no level-bridging scaffolding. In the level-bridging scaffolding condition, participants were explicitly guided to make connections among system levels; by contrast, in the no level-bridging scaffolding condition, the same amount of information was given, but participants were not explicitly guided to make connections.

In the next chapter, the learning topic (“Ideal gas law” system) and research instrument (a simulation-based environment) will be discussed. Readers can understand the variables better after reading the next chapter. The manipulations of these two variables will be extensively discussed in Chapter 5.

## **Section 2. Dependent Variables**

Based on the literature review, different sequencing methods may have effects on different aspects of learning. There are two dependent variables: 1. Knowledge integration 2. Understanding of the deep causal structure.

In this dissertation, knowledge integration refers to students connecting normative scientific concepts and providing coherent explanations to scientific phenomena (Linn, 2006). Understanding of the deep causal structure refers to students being able to construct and transfer a causal model in solving new problems. These two variables are two aspects of deep learning, and are not mutually exclusive. However, knowledge integration measures content knowledge gained in the learning process, while understanding of the deep causal structure measures how well students are able to grasp the implicit causal relations that are more transferrable.

## **Section 3. Hypotheses**

1. The *EM-AM-Mi* sequencing method is more effective in facilitating knowledge integration when compared to the *Mi-AM-EM* and *AM-Mi-EM* sequencing method.



2. The *Mi-AM-EM* sequencing method is more effective in teaching the deep causal structure of a complex system when compared to the *EM-AM-Mi* and *AM-Mi-EM* sequencing method.
3. Level-bridging scaffolding leads to better knowledge integration.
4. Level-bridging scaffolding leads to better understanding of the causal structure.

## **CHAPTER IV.**

### **LEARNING MATERIALS AND INSTRUMENT**

#### **Section 1. Ideal Gas Law as a Complex System**

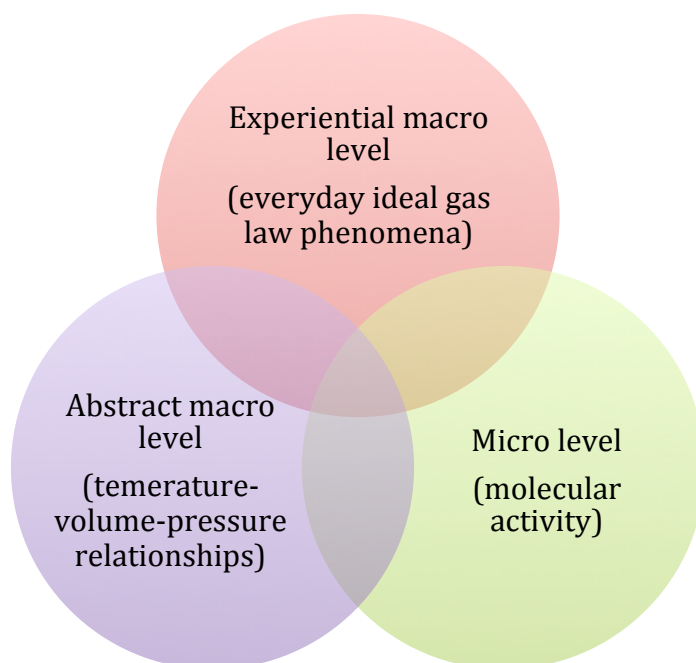
An ideal gas law phenomenon is a complex emergent system with multiple levels. One can understand an idea gas law phenomenon from its experiential macro level, for example, “an aerosol can explodes when the temperature is too high”, or “when one pushes against a balloon, it will become smaller and pop”. Temperature-pressure-volume relationship is an abstract macro level, which is analogous to and explains the experiential macro-level phenomena. The micro level in this system is gas molecular activity. The macro levels of the system emerge from the micro level dynamics.

#### **Section 2. Instructional Goals**

To fully understand this complex system, one needs to understand gas phenomena from all three perspectives, and also understand the implicit causal structure across levels. The sample of this study were middle school students, and they only learned the topic for two class periods, thus the symbolic mathematical model of ideal gas law was not included in the lessons.

Aligned with the two research questions of this study, there were two instructional goals. The first goal was to help students understand and integrate knowledge of system dynamics and processes at all levels. The second goal was to help students understand the

deep causal structure of this complex system, i.e., understand that the pressure change is emergent from the micro-level molecular behaviors, which explains the experiential ideal gas phenomena.



*Figure 5. Three Levels of the Ideal Gas Law System*

Ideally, the author would want the students to construct an emergent-causal schema (Chi et al, 2012). To fully understand the “emergence” concept, students need to provide explanations such as “the macro-level phenomena emerge from ‘all’ molecular activity,” “molecules move randomly and follow simple rules at its local level,” or “there is no central control to each molecule’s behavior,” among others. Studies have shown that the “direct-causal” schema and “central control” schema are very robust at the

secondary school level, and that much conceptual change and diligent training are required before students are able to construct a correct emergent-causal model (Chi et al, 2005).

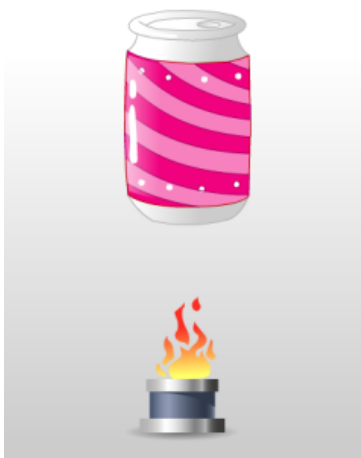
Thus in this particular study, it was not expected that a full emergent-causal model could be constructed within a two-session treatment without explicit instructions on the emergent concepts.

### **Section 3. Simulation-Based Environment as the Research Instrument**

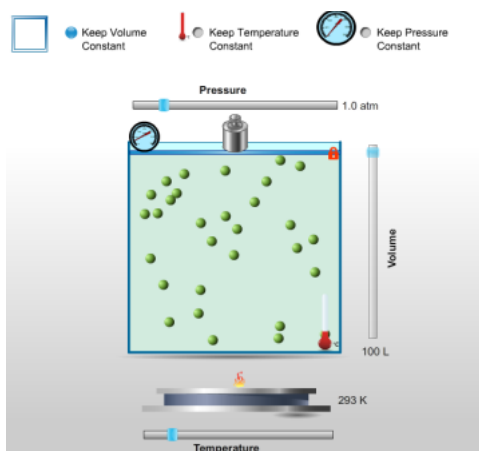
The study employed a simulation-based environment as the research instrument. This simulation-based environment was developed to teach the whole ideal gas laws curriculum unit (three ideal gas laws), but in this study, only two simulations in this environment were used to teach one ideal gas law (temperature-pressure relation when volume is constant).

The first simulation visualized an experiential macro level of the system. Students were able to drag the fire icon towards the can and observe how the can explodes (see *Figure 6*). The second simulation (see *Figure 7*) taught the abstract macro level (temperature-pressure relationship when volume is constant) and the micro-level dynamics (gas molecular activity). The simulations could be displayed separately on two pages, and students switched to either simulation by clicking an arrow button, or they could be displayed on the same page and change simultaneously (see *Figure 8*). This “changing simultaneously” function is called “dynamic link.” The dynamic link

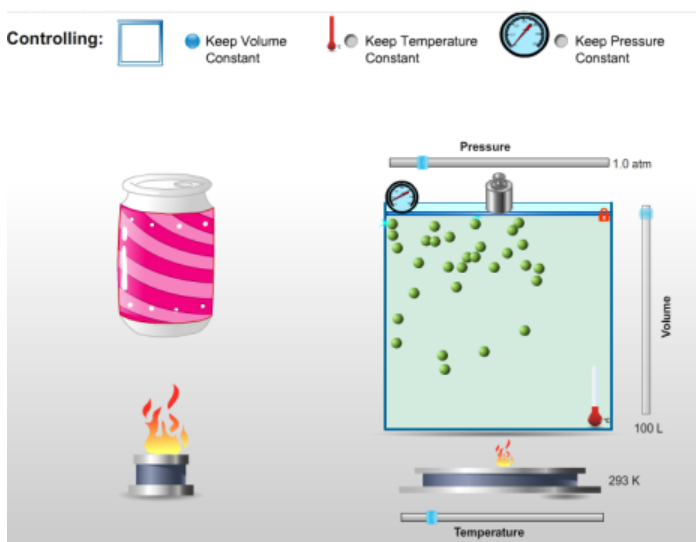
technique has proven beneficial for information integration from multiple representations (van der Meji & de Jong, 2006).



*Figure 6.* Aerosol Can Simulation



*Figure 7.* Gas Container Simulation



*Figure 8. Two Simulations Dynamically Linked*

#### **Section 4. Booklet with Assembled Worksheets as the Learning Materials**

Learning in this project was inquiry-based. There were six learning activities, each including multiple questions. Three learning activities focused on three different levels of the system (see Appendix A for sample questions); the other three learning activities included either inter-level questions or intra-level questions (these will be discussed in chapter 5).

## CHAPTER V.

### METHOD

#### Section 1. Participants

129 seventh graders from two inner-city public middle school participated in this study. The two schools were in the same school district with comparable demographics and performance levels. Six cases were dropped from the sample, as these participants were absent for the second session of the study, so the final sample included 123 participants. 78.9 percent of participants identified themselves as Hispanic, 13.8 percent as black, 4.1 percent as white, and 3.3 percent as other. Mean age of this sample was 12.4 (SD=0.53). 48.8 percent of participants were male, and 51.2 percent were female.

#### Section 2. Design

This study employs a 3x2 factorial design. See *Table 2* for the 6 treatment groups.

*Table 2.* 3x2 Factorial Design

	<i>EM-AM-Mi</i>	<i>Mi-AM-EM</i>	<i>AM-Mi-EM</i>
Level Bridging	Group 1	Group 3	Group 5
No Level Bridging	Group 2	Group 4	Group 6

### **Section 3. Procedure**

Data was collected in the classroom setting on two consecutive days. The total length of the two sessions was around 100 minutes.

#### **Session 1**

1). Pretest: Participants answered two open-ended questions explaining two everyday gas law problems.

2). Within the same classroom, participants were randomly paired up and assigned to a condition. Each pair was assigned a laptop with the simulations and two identical booklets (any two students in a pair were assigned the same condition).

Participants were asked to read the guidance and questions on the worksheets and write down their answers without any group discussion (for better control of extraneous factors). Three research assistants and the science teacher were present to monitor participants' learning progress, help change the simulation interfaces, and solve technical problems. Participants completed around three to four learning activities in the booklet. There was no systematic learning time difference across conditions, and the total learning time was controlled. Groups who finished four learning activities during the first session were asked to stop there and review what they learned during that session until the time was up.



## Session 2

1). Participants were assigned to the same group as Session 1, spent around five minutes reviewing their work from Session 1, and continued learning and completing the rest of the learning activities. Similar to Session 1, no systematic learning time difference across conditions was found. Groups who finished the learning activities were asked to review their work until the session was over.

2). Participants completed a posttest after the learning session. The posttest took around 10 to 15 minutes.

## Section 4. Manipulation

### Sequencing Methods

The sequencing method was manipulated by changing the delivery order of these three system levels: the experiential macro level, the abstract macro level and the micro level. The same learning activities (on worksheets) on three system levels were arranged in different order, and the two corresponding simulations also differed in their order of delivery (see *Figure 9*).

For the *EM-AM-Mi* condition, participants learned the aerosol can explosion phenomenon, then learned the temperature-pressure relationship, and then finally the micro-level dynamics (molecular activity).

For the *Mi-AM-EM* condition, participants learned the micro level first (molecular activity), then the abstract macro level (temperature-pressure relationship), and finally the experiential macro level (aerosol can explosion phenomenon).

For the *AM-Mi-EM* condition, participants first learned the abstract macro level (temperature-pressure relationship), then the micro level (molecular activity) and finally the experiential macro level (aerosol can explosion phenomenon). This sequencing approach is like learning the abstract system first, and then applying it to an everyday problem.

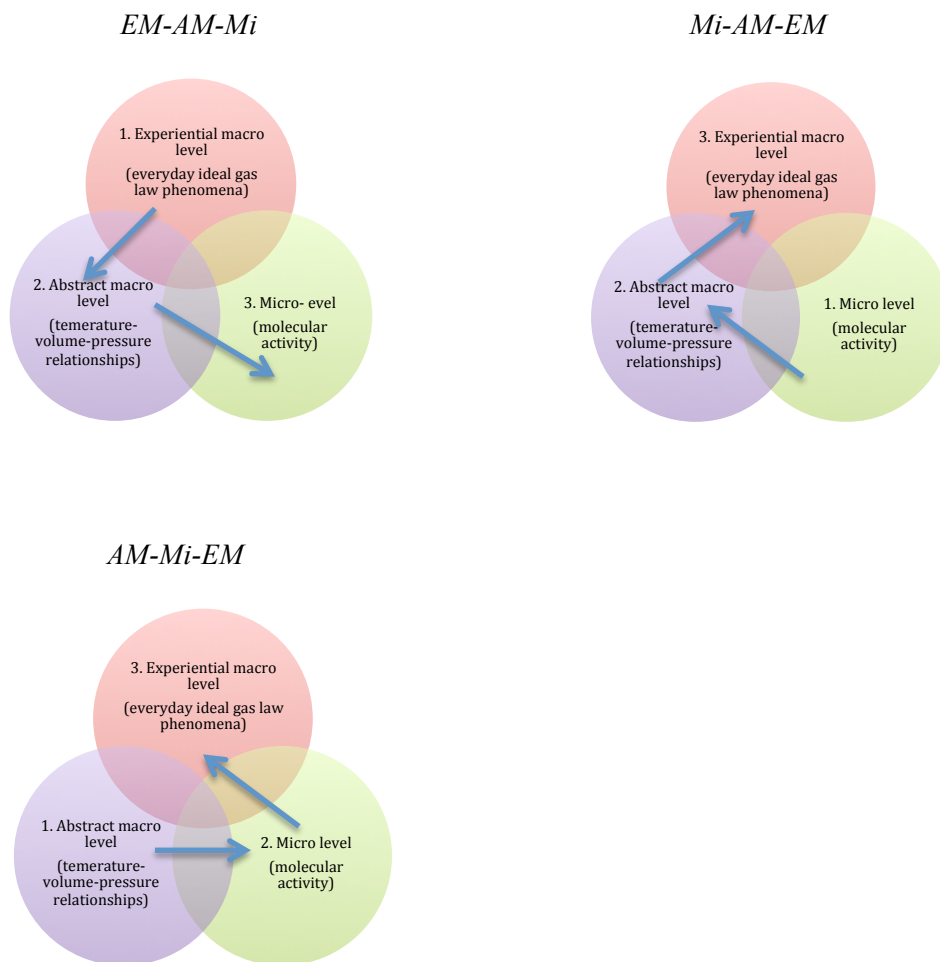


Figure 9. Manipulation of the Sequencing Methods

## Level-Bridging Scaffolding

Level-bridging scaffolding targeted at connection making across levels was another variable the author operationalized and tested in this study. For the level-bridging scaffolding condition,

1). Inter-level questions were inserted among learning activities; i.e., every time participants learned two system levels, they were asked to answer inter-level questions designed for level bridging.

2). The two simulations were dynamically linked for the final learning activity (see *Figure 8* in chapter 4).

For the no level-bridging scaffolding condition,

1). Intra-level questions were inserted among learning activities; i.e., every time participants learned one system level, they were asked to answer intra-level questions designed to help them summarize the concepts they learned at that system level.

2). The two simulations were not dynamically linked and displayed separately for the final learning activity.

The set of inter-level questions and intra-level questions was manipulated so that the same amount of information was given across conditions. (Please see *Table 3* for the two sets of questions.) Where each question was inserted also depended on the sequencing method condition.

Table 3. Inter-Level Questions vs. Intra-Level Questions

Inter-level questions	Intra-level questions
1. What is the relationship between temperature and pressure? Use what you learned about temperature and pressure from the gas container presentation, explain why the aerosol can explodes?	1. Explain why the aerosol can explodes?
2. How do gas molecules behave? Use what you learned about gas molecules; explain why as temperature rises, pressure inside the container also rises?	2. Use what you learned about temperature and pressure from the gas container presentation, explain what is the relationship between temperature and pressure?
3. Use the knowledge of gas molecules; explain what happens to the gas pressure inside the aerosol can as you drag the fire closer? Explain why the aerosol can explodes?	3. Use the knowledge of gas molecules; explain how do gas molecules behave?  4. Explain what happens to the aerosol can as you drag the fire closer?  5. What did you learn from the aerosol can presentation?  6. As temperature rises, pressure also rises, is this correct?  7. What did you learn about gas molecules?

One limitation of this manipulation was that it tended to be difficult to tease apart the effects of the inter-level questions and the dynamic link of the two simulations in the final task. However, this study treated level-bridging scaffolding as a construct, and the

effects of different forms of scaffolding can be tested in further studies; e.g. inter-level questions as external scaffolding, dynamically-linked simulations as software-realized scaffolding, and other potential scaffolding methods.

Please see *Table 4* for a clear view of how the worksheets were organized and where the inter-level and intra-level questions were inserted for each condition.

Table 4. Manipulations of Two Variables

<i>EM-AM-Mi</i>		<i>Mi-AM-EM</i>		<i>AM-Mi-EM</i>	
Level-Bridging	No Level-Bridging	Level-Bridging	No Level-Bridging	Level-Bridging	No Level-Bridging
Experiential Macro Level	Experiential Macro Level	Micro Level	Micro Level	Abstract Macro Level	Abstract Macro Level
	<i>Intra-level question 1</i>				Intra-level question 2
Abstract Macro Level	Abstract Macro Level	Abstract Macro Level	Abstract Macro Level	Micro Level	Micro Level
<i>Inter-level question 1</i>	<i>Intra-level question 2</i>	<i>Inter-level question 2</i>	<i>Intra-level question 2</i>	Inter-level question 2	Intra-level question 3
Micro Level	Micro level	Experiential Macro Level	Experiential Macro Level	Experiential Macro Level	Experiential Macro Level
<i>Inter-level question 2</i>	<i>Intra-level question 3</i>	<i>Inter-level question 1</i>	<i>Intra-level question 1</i>	Inter-level question 1	Intra-level question 1
<i>Inter-level question 3</i> With two simulations dynamically linked	<i>Intra-level question 4, 5, 6, 7</i> With two simulations displayed on separate pages	<i>Inter-level question 3</i> With two simulations dynamically linked	<i>Intra-level question 7, 6, 5, 4</i> With Two simulations displayed on separate pages	Inter-level question 3 With two simulations dynamically linked	Intra-level question 6, 7, 5, 4 With two simulations displayed on separate pages

*\*The inter-level and intra-level questions are numbered because the same question could be inserted at different times across conditions.*

*In the final activity (last row of the chart), simulations were either dynamically linked or displayed on separate pages, which is a part of the level-bridging manipulation. The order of intra-level questions 4, 5, 6, and 7 is arranged according to the sequencing method the group received.*

## **Section 5. Measures**

### **Pretest**

The pretest included two essay questions asking the participants to explain two ideal gas law problems: “using ice pack to reduce tooth pain,” and “car tires are more likely to explode in the summer than in the winter.” No extra system information about ideal gas law was provided in the pretest. As a pilot study indicated, priming the participants with any level of the system might disrupt the manipulation of sequencing methods.

### **Posttest**

The posttest included four parts: recall of system knowledge, comprehension of system knowledge, recall of simulation events, and transfer tasks. Recall and comprehension of system knowledge measured low-level and high-level of knowledge integration, and the two transfer tasks measured understanding of the deep causal structure. Participants’ performance on knowledge integration and understanding of the deep causal structure were analyzed to test the hypotheses. Recall of simulation events measured shallow learning. This part was included in the measures because the author would like to differentiate shallow learning from knowledge integration.

Table 5. Posttest Measures

Constructs	Measured on
Knowledge Integration	Low-level: Recall of system knowledge High-level: Comprehension of system knowledge
Shallow learning	Recall of simulation events
Understanding of the Deep Causal Structure	Transfer tasks

*Recall of System Knowledge: Low-Level Knowledge Integration*

This task included one short-answer question, two open-ended questions, and one labeling question measuring recall of system structural and behavior knowledge. Because the experiential macro level function (aerosol can explodes) was very easy, this task only included questions about the abstract macro-level and micro-level knowledge.

1. Gas is composed of\_\_\_\_\_
2. How do gas molecules behave? How do gas molecules interact with each other?
3. Label the variables on the picture (In this labeling question, a snapshot of the simulation was given, and students were expected to correctly label temperature, volume and pressure, and their unit names)



In question 3, students needed to label all three variables correctly to get the one point, and to label all three unit names correctly to get the other point. This question measured structural knowledge of the abstract macro level.

### *Comprehension: High-Level Knowledge Integration*

The comprehension task included four open-ended questions measuring high-level knowledge integration. Unlike the recall of system knowledge task, this task required participants to coherently explain the aerosol can phenomenon, the abstract macro-level “pressure” concept, and to demonstrate knowledge of the abstract macro level, the micro level, and cross-level causality.

1. *You throw an aerosol can into the fire and it explodes. Please explain how that happens.*
2. *What is gas pressure? How do you understand gas pressure?*
3. *When the volume of a certain amount gas stays the same, the higher the temperature, the \_\_\_\_\_ the gas pressure. How does that happen?*
4. *If you want to decrease gas pressure, what should you do? Why?*

### *Recall of Simulation Events: Shallow Learning*

The recall of simulation events task included one open-ended question measuring shallow learning. Two snapshots of the gas container simulation (see *Figure 7* in chapter

4) were given and participants were asked to describe what happened between Time A and Time B.

*Transfer: Understanding of the Deep Causal Structure*

In the transfer task, the same two ideal gas law problems as in the pretest were used to measure understanding of the deep causal structure of the system. Different from the comprehension questions, these two questions required students to recognize these problems as ideal gas law phenomena, and then transfer a causal model to explain the phenomena.

*1. An infected tooth forms a tiny space that fills with gas. The gas puts pressure on the nerve of the tooth, causing a toothache. Which of the following should the patient choose to relieve pain?*

*A. Moist heat*

*B. Ice pack*

*Why? Explain.*

*2. Car tires are more likely to pop in the summer than in the winter. Please explain why that happens.*

## Coding Scheme

A coding scheme was developed for the pre- and posttests. For each open-ended question, all possible system concepts and knowledge units were listed in the coding scheme, and participants' answers were coded on the presence and absence of each item. Raters were trained before they started coding. Two raters blind to the condition independently coded each part of the pre- and posttests. Inter-rater reliability was above 95 percent for all parts of the pre- and posttests.

Partial coding scheme:

*How do gas molecules behave? How do gas molecules interact with each other?*

Coding scheme:

*Mention molecules move randomly (1)*

*Mention speed of molecules (1)*

*Mention the correct relationship between temperature and speed of molecules (1)*

*Mention gas molecules bounce off each other (1)*

*Mention gas molecules bounce off the container walls (1)*

*What is gas pressure? How do you understand gas pressure?*

Coding scheme:

*Mention increased pressure causes the aerosol can to explode (1)*

*Mention the correct causal relationship between temperature and speed of molecules (1)*

*Mention speed of gas molecules (1)*

*Mention gas molecules bouncing behavior (1)*

*Car tires are more likely to pop in the summer than in the winter. Please explain why that happens.*

*Coding scheme:*

*Mention “temperature higher in summer than in winter” (0.5)*

*Mention “increased pressure as the cause to the phenomenon (1)*

*Mention correct causal relationship between Temperature and Pressure (1)*

*Mention gas molecules behaviors (speed change, bouncing) (1) or only molecules without correct behavior knowledge (0.5)*

*Mention the correct causal relationship between molecular activity and pressure (1)*

\*Two knowledge units are relatively easier than the other, thus were only assigned 0.5

## **Statistical Analysis Method**

This study used quantitative statistical analysis. An ANOVA test was conducted to compare the pretest scores across groups and establish equivalency. The pretest scores were then treated as a covariate in comparing the posttest scores across groups. Two-way ANCOVA with Helmert contrasts were conducted to test the hypotheses. In the next chapter, the results will be presented and discussed.

## CHAPTER VI.

### RESULTS

#### Section 1. Inter-Rater Reliability

As most of the pre- and posttest questions were open-ended, participants' answers were coded based on the presence and absence of a list of system knowledge units. Two raters blind to the conditions independently coded each part of the pre and posttest. Inter-rater reliability was above 95 percent for all parts of the pre- and posttest. Disagreement was resolved through discussion between the two raters.

*Table 6 . Inter-Rater Reliability*

	Inter-Rater Reliability
Pretest	98.4%
Recall of system knowledge	95.7%
Comprehension	95.4%
Recall of simulation events	96.9%
Transfer	95.7%

#### Section 2. Pretest Scores

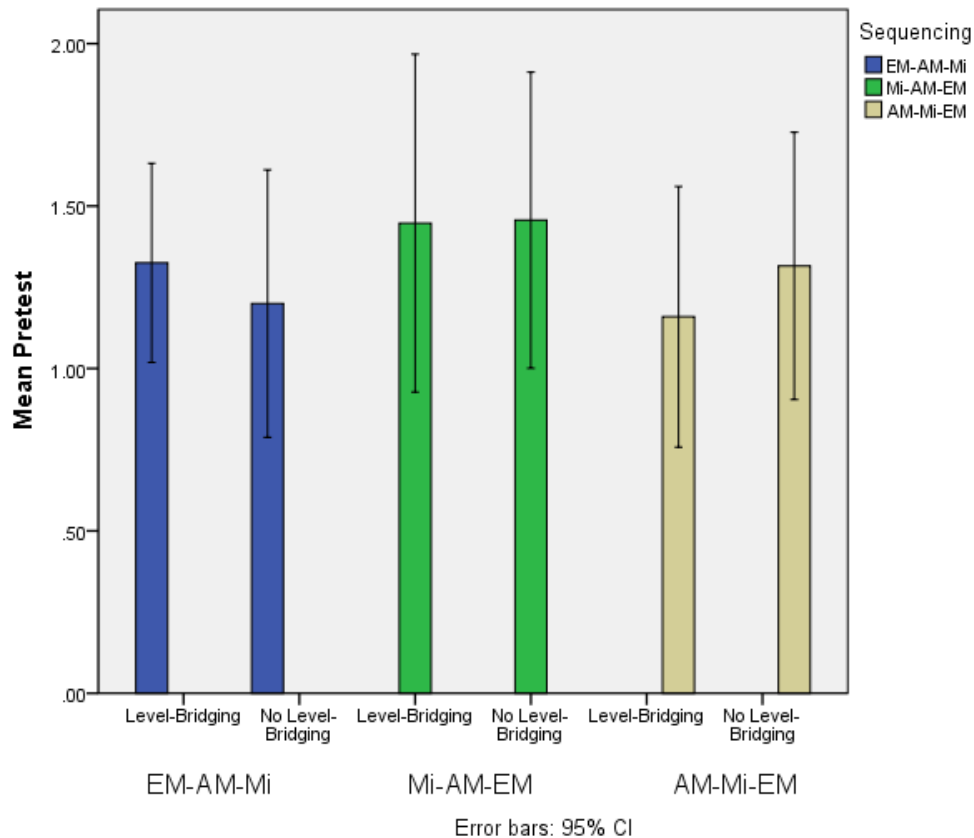
The pretest included two everyday ideal gas law problems requiring participants to provide scientific explanation. The answers were coded based on the absence or

presence of important system knowledge units. The highest possible score was 10. Inter rater agreement was 98.4 percent.

A comparison among the six groups showed that there were no significant differences across conditions (for mean scores, see *Table 7*). Most of the participants did not include important scientific system knowledge to explain the everyday ideal gas law phenomena, and the mean scores were low. Pretest scores did not significantly differ across sequencing methods:  $F(2, 117) = 0.674$ ,  $p = 0.512$ , or across level-bridging conditions,  $F(1, 117) = 0.007$ ,  $p = 0.935$ . No interaction was found:  $F(2, 117) = 0.238$ ,  $p = 0.789$ . The pretest scores were used to establish equivalency and used as a covariate in further analysis.

*Table 7.* Pretest Mean Scores (maximum possible score: 10)

	<i>EM-AM-Mi</i>	<i>Mi-AM-EM</i>	<i>AM-Mi-EM</i>	Marginal
Level-Bridging	1.33(0.65) N=20	1.45(1.08) N=19	1.16(0.90) N=22	1.30(0.89) N=61
No Level-Bridging	1.20(0.88) N=20	1.46(1.05) N=23	1.32(0.85) N=19	1.33(0.93) N=62
Marginal	1.26(0.77) N=40	1.45 (1.05) N=42	1.23(0.87) N=41	Total 1.32(0.91) N=123



*Figure 10. Pretest Mean Scores*

### Section 3. Posttest Scores

As most of the questions in the pre- and posttests were open-ended, all possible knowledge units were included in the coding scheme (the possible maximum score was high). However, usually participants did not voluntarily include everything they understand when answering open-ended questions. Thus, the average score of each part was relatively low when compared to the possible maximum score.

The posttest measured three aspects of learning: Knowledge integration, shallow learning and understanding of the deep causal structure. Knowledge integration and

understanding of the deep causal structure were two dependent variables measured to test the hypotheses. Shallow learning was measured because the author would like to tease apart this construct from knowledge integration.

### **Knowledge Integration**

Knowledge integration was measured through recall of system knowledge (low-level) and comprehension of system knowledge (high-level). The results were analyzed to test the following hypotheses:

*Hypothesis 1. The EM-AM-Mi sequencing method produces better knowledge integration when compared to the Mi-AM-EM and AM-Mi-EM sequencing methods.*

*Hypothesis 3. Level-bridging scaffolding leads to better knowledge integration.*

As an inferential test, two-way ANCOVA test with Helmert contrasts were conducted. The main effects of sequencing methods, level-bridging scaffolding, and their interaction effects were analyzed. To provide answers to Hypothesis 1, the first contrast compared the *EM-AM-Mi* to the average of the other two sequencing methods, while the second contrast compared the *Mi-AM-EM* and *AM-Mi-EM* sequencing methods.

In general, results of recall of system knowledge and comprehension of system knowledge provided evidence for Hypotheses 1 and 3.



*Recall of System Knowledge (Possible Maximum Score =8)*

This part measured participants' recall of system knowledge with questions such as "How does molecules behave?" and "How do molecules interact with each other?" Participants' answers were coded on the presence or absence of a list of knowledge units associated with each question. The possible maximum score was 8. Two statistical outliers were converted to the 98-percentile value of the sample distribution. (For descriptive data, please see *Table 8* and *Figure 11*). Two-way ANCOVA with Helmert contrasts were conducted to test Hypothesis 1 and Hypothesis 3.

Pretest scores were somewhat correlated with recall of system knowledge. The association was marginally significant:  $F(1, 116) = 3.36, p = 0.069$ . No interaction was found between the sequencing methods and level-bridging scaffolding:  $F(2, 116) = 0.212, p = .847$ , indicating the effects of sequencing methods and level-bridging scaffolding were additive on recall of system knowledge.

The first contrast tested the difference between the *EM-AM-Mi* and the other two sequencing methods, and the second contrast tested the difference between the *Mi-AM-EM* and *AM-Mi-EM* methods. For contrast results, see *Table 9*.

As evidence for Hypothesis 1, contrasting the *EM-AM-Mi* vs. the average of the other two sequencing methods showed that utilizing the *EM-AM-Mi* sequencing method led to better recall of system knowledge over the other two sequencing methods,  $t(116)=2.56, p = 0.012 < 0.05$ . The contrast between the *Mi-AM-EM* and the *AM-Mi-EM* was not significant,  $t(116)=0.133, p = 0.894$ .

As evidence for Hypothesis 3, level-bridging scaffolding did show significant positive main effects on recall of system knowledge:  $F(1, 116) = 7.24, p = 0.008 < 0.05$ .

In general, the results also showed that the *EM-AM-Mi* method and level-bridging scaffolding had significant additive effects in facilitating recall of system knowledge (low-level knowledge integration).

*Table 8. Recall of System Knowledge Mean Scores*

	<i>EM-AM-Mi</i>	<i>Mi-AM-EM</i>	<i>AM-Mi-EM</i>	Marginal
Level-bridging	4.30(1.08) N=20	3.45(1.19) N=19	3.50(1.53) N=22	3.77(1.26) N=61
No Level-bridging	3.45(1.19) N=20	3.00(1.65) N=23	3.00(1.20) N=19	3.14(1.37) N=62
Marginal	3.88(1.20) N=40	3.24(1.38) N=42	3.27(1.40) N=41	Total 3.46(1.35) N=123
<p><i>Note: The mean scores represent the average number of knowledge units provided, and the numbers in the parentheses are the corresponding standard deviation values.</i></p>				

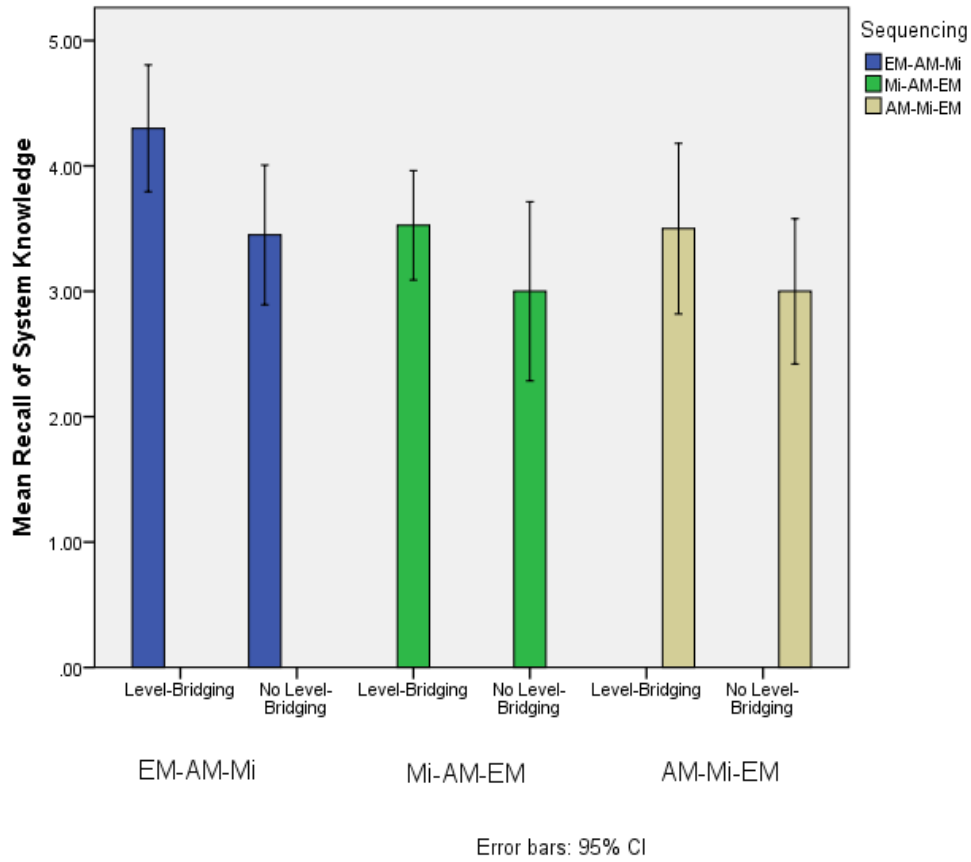


Figure 11. Recall of System Knowledge Mean Scores

Table 9. Recall of System Knowledge Contrasts Results

	Recall of System Knowledge
<b>Contrast 1:</b> <i>EM-AM-Mi</i> vs. Other	$t(116)=2.56$ Sig. $p=0.012<0.05$
<b>Contrast 2:</b> <i>Mi-AM-EM</i> vs. <i>AM-Mi-EM</i>	$t(116)=0.13$ Sig. $p=0.894$

In order to see how the items differentiated in terms of recall of system knowledge across conditions, the percentage of participants getting each item correct was calculated (See Appendix B).

The descriptive item analysis provided some interesting findings: In the *EM-AM-Mi* condition, grounding abstract macro-level concepts in everyday experience supported recall of macro-level structural knowledge (i.e., temperature, pressure and volume as three factors of the abstract macro level), and level-bridging scaffolding also had an additive effect in this area. While in integrating micro-level structural and behavior knowledge, although the *EM-AM-Mi* sequencing method produced higher total scores, participants might have only focused on visually salient molecular activity related to the concrete macro-level factor of “temperature,” such as “molecule speed changes based on temperature,” or “molecules bump more when temperature is high.” However, participants in this condition actually recalled less pieces of knowledge related to the abstract macro-level factor of “pressure”, such as “molecules move randomly,” and “molecules bumping into the walls,” from both of which pressure emerges. These pieces of knowledge were required in constructing a correct causal model of the system. Level-bridging scaffolding facilitated recall of micro-level behavior knowledge, both salient and implicit, and had more sustainable effects on recall of system knowledge when compared to the sequencing methods variable.

It should be noted that this measure did have some limitations. Although the total scores supported the hypotheses, not all items showed the same pattern. Specifically, for some items, there was a floor effect; thus, they did not have strong discriminatory power.

#### *Comprehension (Possible Maximum Score =15)*

This part measured comprehension of system knowledge, with questions posed to students including, “Explain the aerosol can phenomena” and “Explain the gas pressure

concept,” among others. The results of this part provided statistically significant evidence for Hypothesis 3: Level-bridging scaffolding leads to better knowledge integration. The results showed more positive results from the *EM-AM-Mi* sequencing method than from the other two sequencing methods, but were not significant enough to support Hypothesis 1: The *EM-AM-Mi* sequencing method produces better knowledge integration when compared to the other two sequencing methods.

For the mean scores of comprehension, please see *Table 10* and *Figure 12*. Two-way ANCOVA with Helmert contrasts was conducted as an inferential test. The first contrast tested the difference between the *EM-AM-Mi* method and the average of other two sequencing methods, and the second contrast tested the difference between the *Mi-AM-EM* and *AM-Mi-EM* methods (see *Table 11* for the contrasts results).

Pretest scores were significantly associated with comprehension of system knowledge,  $F(1, 116) = 8.51, p = .004$ . The interaction between the sequencing methods variable and level-bridging scaffolding was not significant,  $F(2, 116) = 0.049, p = .952$ , indicating the effects of the sequencing methods and level-bridging scaffolding on comprehension were additive.

Although there was a positive trend, the *EM-AM-Mi* sequencing method did not show significant better comprehension performance when compared to the other two sequencing methods,  $t(116)=1.46, p = 0.146$ . There was no difference between the *Mi-AM-EM* and the *AM-Mi-EM* sequencing method either,  $t(116)=0.067, p=0.947$ .

Significant main effects of level-bridging scaffolding, however, were found:  $F(1, 116) = 4.45, p = 0.037 < 0.05$ . To determine which items had the discriminant power, percentages of participants getting each item correctly were calculated (see Appendix C).

The item analysis indicated that level-bridging scaffolding led to better understanding of abstract macro-level concepts (e.g., conceptually understand “pressure”), the abstract macro-level relationship (i.e., the temperature-pressure relationship), and also of micro-level behavior knowledge (e.g., gas molecules move faster or slower in response to temperature). Some items, however, especially those relating to cross-level causal knowledge (e.g., molecular activity causes pressure to go up), had a floor effect, and thus did not have discriminant power. However, the above discussion was based on descriptive analysis, and may lack statistical power.

*Table 10. Comprehension Mean Scores*

	<i>EM-AM-Mi</i>	<i>Mi-AM-EM</i>	<i>AM-Mi-EM</i>	Marginal
Level-Bridging	3.97(1.41) N=20	3.53(1.57) N=19	3.34(2.01) N=22	3.60(1.70) N=61
No Level-Bridging	3.20(1.64) N=20	2.89(1.27) N=23	2.92(1.98) N=19	3.00(1.61) N=62
Marginal	3.58(1.56) N=40	3.18(1.43) N=42	3.15(1.98) N=41	Total 3.30(1.68) N=123
<i>Note: The mean scores represent the average number of knowledge units provided, and the numbers in the parentheses are the corresponding standard deviation values.</i>				

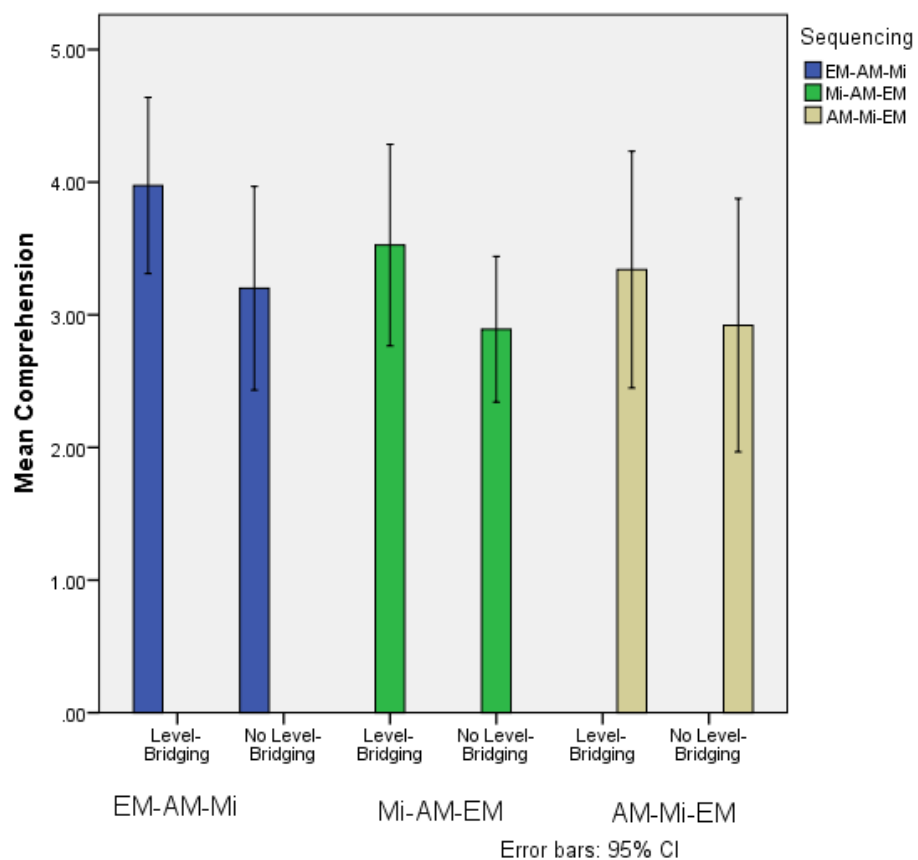


Figure 12. Comprehension Mean Scores

Table 11. Comprehension Contrasts Results

	Comprehension
<b>Contrast 1:</b> <i>EM-AM-Mi</i> vs. Other	$t(116)=1.46$ Sig. $p=0.146$
<b>Contrast 2:</b> <i>Mi-AM-EM</i> vs. <i>AM-Mi-EM</i>	$t(116)= 0.067$ Sig. $p=0.947$

## Shallow Learning

### *Recall of Simulation Events (Possible Maximum Score = 6)*

This part measured superficial recall of simulation events. Two snapshots of the gas container simulation were given, and participants were asked, “What happens from Time A to Time B?” One simulation event was assigned one point.

For mean scores of the recall of simulation events task, please see *Table 12* and *Figure 13*. Two-way ANCOVA with Helmert contrasts were conducted. The first contrast tested the difference between the *EM-AM-Mi* sequencing method and the average of other the two sequencing methods, and the second contrast tested the difference between the *Mi-AM-EM* and *AM-Mi-EM* methods.

Pretest score as a covariate was not significant:  $F(1, 116) = 1.11, p = 0.29$ . The interaction between the first contrast (*EM-AM-Mi* vs. Other) and level-bridging scaffolding was significant,  $t(116)=2.02, p=0.045$  (see *Table 13*). The results indicated that the *EM-AM-Mi* & no level-bridging treatment group recalled more simulation events as compared to the other treatment groups.

When comparing recall of system knowledge and recall of simulation events, we may find that the *EM-AM-Mi* sequencing method led to better recall in general. Given level-bridging scaffolding, participants were more likely to integrate important system structural and behavior knowledge. In the no level-bridging scaffolding condition, however, participants might focus more on those superficial simulation events. Recall of simulation events was measuring shallow learning, a construct other than knowledge integration. There was no significant correlation between the recall of simulation events



task and the two tasks measuring knowledge integration (Please see Appendix E for a correlation matrix of the three tasks).

*Table 12. Recall of Simulation Events Mean Scores*

	<i>EM-AM-Mi</i>	<i>Mi-AM-EM</i>	<i>AM-Mi-EM</i>	Marginal
Level-Bridging	1.75(0.55) N=20	1.79(0.71) N=19	1.86(0.83) N=22	1.80(0.70) N=61
No Level-Bridging	2.30(0.66) N=20	1.83(0.83) N=23	1.84(0.60) N=19	1.98(0.74) N=62
Marginal	2.02(0.66) N=40	1.81(0.77) N=42	1.85(0.73) N=41	Total 1.89(0.72) N=123
<i>Note: The mean scores represent the average number of knowledge units provided, and the numbers in the parentheses are the corresponding standard deviation values.</i>				

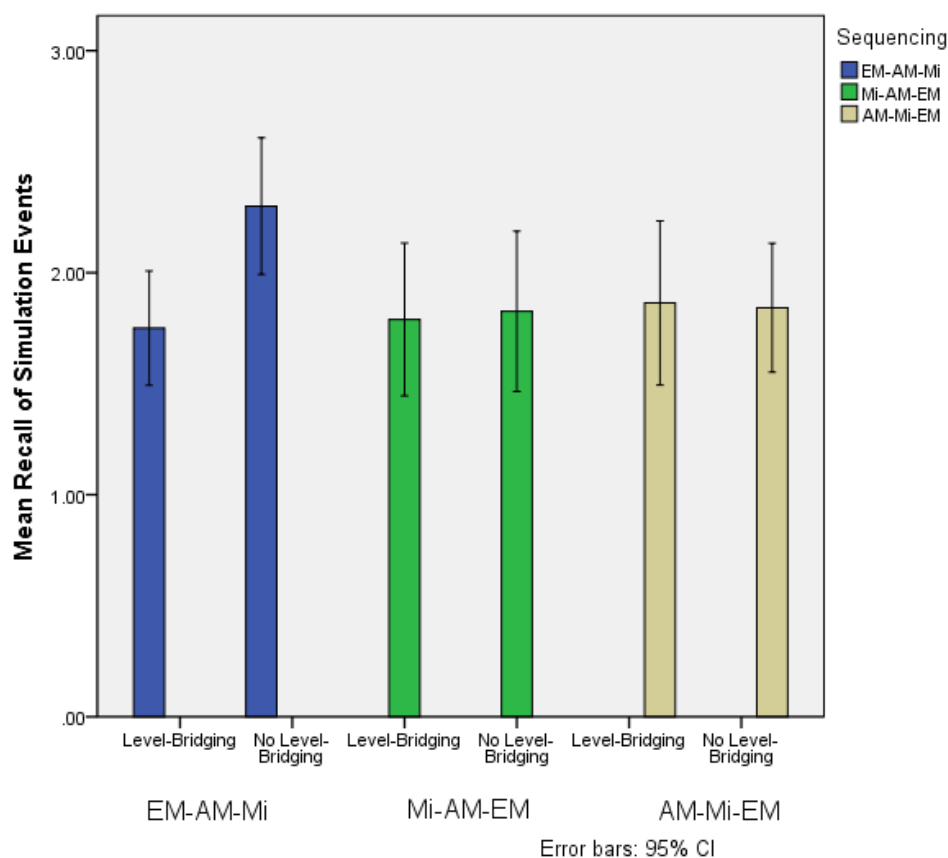


Figure 13. Recall of Simulation Events Mean Scores

Table 13. Recall of Simulation Events Contrasts Results

	Recall of Simulation Events
<b>Contrast 1:</b> <i>EM-AM-Mi</i> vs. Other	$t(116)=1.46$ Sig. $p=0.147$
<b>Contrast 2:</b> <i>Mi-AM-EM</i> vs. <i>AM-Mi-EM</i>	$t(116)=0.389$ Sig. $p=0.698$
<b>Contrast 1 x Level-bridging scaffolding</b>	$t(116)=2.03$ Sig. $p=0.045<0.05$
<b>Contrast 2 x Level-bridging scaffolding</b>	$t(116)=0.22$ Sig. $p=0.826$

## Knowledge Integration vs. Shallow Learning

To sum up, the results from recall of system knowledge supported *Hypothesis 1*: *The EM-AM-Mi sequencing method produces better knowledge integration when compared to the other two sequencing methods*. Results from comprehension were not significant enough to support *Hypothesis 1*. The results from recall of system knowledge and comprehension supported *Hypothesis 3*: *“Level-bridging” scaffolding leads to better knowledge integration*.

When comparing recall of system knowledge and comprehension of system knowledge, we could find that the data patterns were similar, except that the effects of the *EM-AM-Mi* sequencing method were not statistically significant in comprehension. The author concludes that the effects of the *EM-AM-Mi* sequencing method were on low-level knowledge integration; however, its effects were not very robust on deep learning. Level-bridging scaffolding was effective on both low-level and high-level knowledge integration.

Descriptive item analysis also indicated that, although the *EM-AM-Mi* method facilitated recall of system knowledge in general, it did not facilitate recall of micro-level behavior knowledge that was implicit but important for constructing a causal model. However, the level-bridging scaffolding facilitated recall of both salient and implicit micro-level behavior knowledge. The effects of level-bridging scaffolding on knowledge integration were more sustainable.

Recall of simulation events was measuring shallow learning, a construct different from knowledge integration, thus recall of simulation events did not show a similar

pattern as the other two measures. The correlation matrix of the measures (see Appendix E) showed no correlation between recall of simulation events and the other two knowledge integration measures. When comparing recall of system knowledge and recall of simulation events, we could find that the *EM-AM-Mi* sequencing method produced better recall in general; however, when given level-bridging scaffolding, participants recalled more important system knowledge, while in the no level-bridging scaffolding condition, participants recalled more superficial simulation events. This also demonstrated the importance of level-bridging scaffolding on deep learning.

### **Understanding of the Deep Causal Structure**

Transfer tasks were used to measure understanding of the deep causal structure. This measure included the same two everyday ideal gas law problems from the pretest. The results were analyzed to test the following hypotheses:

*Hypothesis 2: The Mi-AM-EM sequencing method produces better understanding of the deep causal structure when compared to the EM-AM-Mi and AM-Mi-EM sequencing methods.*

*Hypothesis 4: Level-bridging scaffolding facilitates understanding of the deep causal structure.*

*Transfer (Possible Highest Score=10)*

In Appendix F, readers can find some example answers to the transfer questions.

Participants' answers were coded on a list of important concepts that should be in a correct causal model. The answers were also coded on the explicit causal statements about the system. These two coding schemes produced the same pattern, except there was a floor effect when the answers were coded only on the explicit causal statements. Thus the first coding scheme (important system concepts) was utilized.

For the mean scores of transfer performance, please see *Table 14* and *Figure 14*. Two statistical outliers were converted to the 98th percentile of the sample mean. Two-way ANCOVA with Helmert contrasts was conducted to test Hypothesis 2 and 4. Two different contrasts were conducted to test Hypothesis 2. The first contrast tested the difference between the *Mi-AM-EM* sequencing and the average of the other two sequencing methods, and the second contrast tested the difference between the *EM-AM-Mi* and *AM-Mi-EM* sequencing methods. The interaction effects between each contrast and level-bridging scaffolding were also tested (see *Table 15*).

*Table 14. Transfer Mean Scores*

	<i>EM-AM-Mi</i>	<i>Mi-AM-EM</i>	<i>AM-Mi-EM</i>	Marginal
Level-Bridging	1.95(1.15) N=20	2.97(1.72) N=19	1.80(1.46) N=22	2.21(1.34) N=61
No Level-Bridging	1.85(1.55) N=20	1.85(1.22) N=23	1.63(1.30) N=19	1.78(1.34) N=62
Marginal	1.90(1.35) N=40	2.35(1.56) N=42	1.71(1.34) N=41	Total 2.00(1.45) N=123

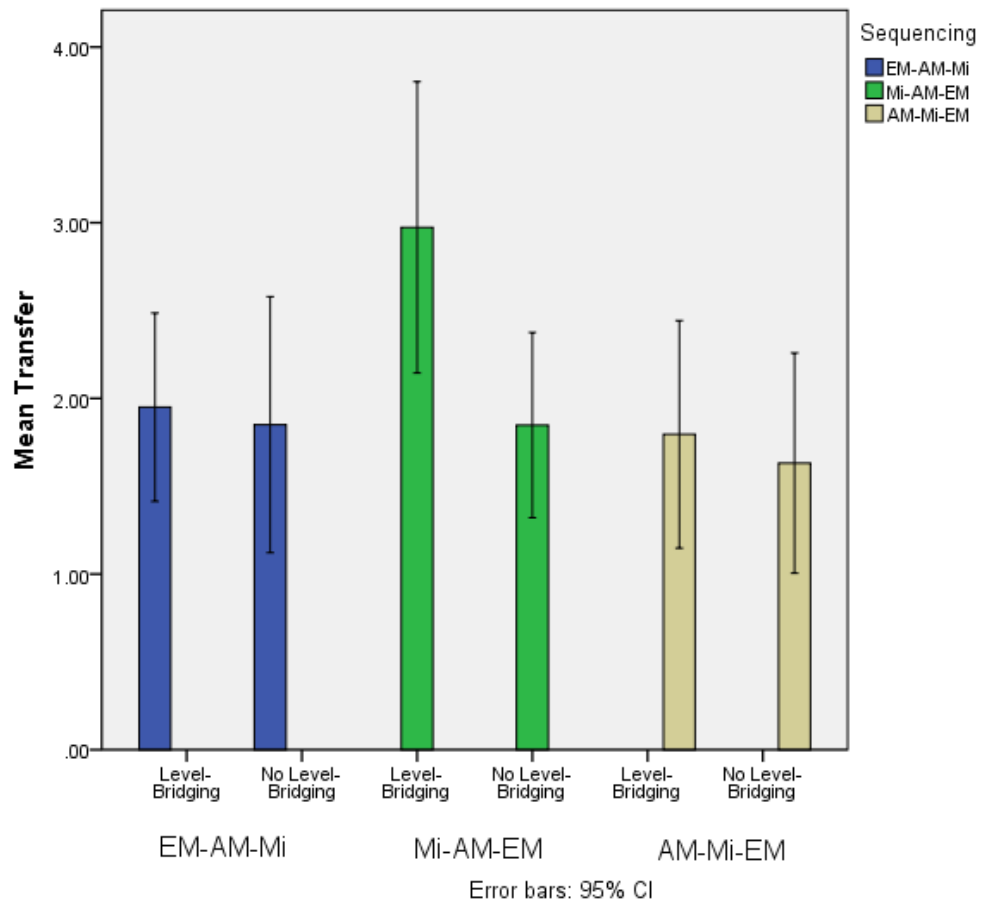


Figure 14. Transfer Mean Scores

Pretest scores were significantly associated with the transfer task scores,  $F(1, 116) = 27.7$ ,  $p < 0.001$ . The interaction of the first contrast (*Mi-AM-EM* vs. other) and level-bridging scaffolding was significant,  $t(116)=2.04$ ,  $p=0.044$ . This indicated that the *Mi-AM-EM* & level-bridging scaffolding treatment group outperformed other treatment groups.

Table 15. Transfer Contrasts Results

	<b>Transfer</b>
<b>Contrast 1:</b> <i>Mi-AM-EM</i> vs. Other	t(116)=1.92 Sig. p=0.058
<b>Contrast 2:</b> <i>EM-AM-Mi</i> vs. <i>AM-Mi-EM</i>	t(116)=0.60 Sig. p=0.55
<b>Contrast 1 x Level-Bridging</b>	t(116)=2.04 Sig. p=0.045<0.05
<b>Contrast 2 x Level-Bridging</b>	t(116)=0.448 Sig. p=0.655

Transfer task results provided evidence for Hypotheses 2 and 4. The data pattern in this part indicated that the *Mi-AM-EM* sequencing method with level-bridging scaffolding was the best combination for learning the deep causal structure of the system.

Descriptive item analysis was conducted to determine on which aspects this treatment group performed better (see Appendix D). Participants in the *Mi-AM-EM* & level-bridging scaffolding group transferred more macro-level concepts and causal knowledge (i.e., temperature, pressure, and temperate-pressure relationship), as well as more micro-level behavior knowledge (i.e., molecular activity). Although the percentage was low, participants in the *Mi-AM-EM* & level-bridging group were more likely than their peers in other groups to transfer the causal relationship between the micro-level dynamics and the macro-level concept of “gas pressure.” As can be seen, a larger percentage of participants in this group used the “pressure” concept to explain two everyday ideal gas law problems, and many also mentioned “gas molecules’ behaviors” in their responses.

When comparing the pretest and this part, we can see that it was inherently difficult for students to transfer the causal model. The transfer questions were the same as the pretest questions, but the average pre-post gain was only 0.68 (SD = 1.33),  $t(122)=5.66$ ,  $p < 0.001$ . Although the difference was statistically significant, the improvement size was small.

In general, participants in the *Mi-AM-EM* & level-bridging group performed better in the transfer tasks than other treatment groups. Participants in this group were more able to recognize the problems as ideal gas law system problems and transfer the causal knowledge. However, explanations about emergence concepts (e.g., all molecules behave and interact simultaneously, from which pressure emerges) were very rare.



## **CHAPTER VII.**

### **DISCUSSION**

Complex systems are difficult to learn. As instructors, we want students to integrate system content knowledge, to have a “levels” lens to analyze complex system phenomena, and also to understand the implicit causal structures. In chapter 2, the nature of complex systems and three major learning difficulties are discussed: 1. It is difficult to integrate a large amount of system knowledge; 2. It is difficult to make sense of abstract system levels; and, 3. It is difficult to understand the deep causal structure in a complex system. Learning environments and external scaffolding are both important in tackling these learning difficulties. This is the basic conceptual framework for this dissertation project.

Ideal gas law is a complex chemical system. Based on the conceptual framework, the instructional goals and the simulation-based learning environment are discussed in chapter 4.

The study methodology and results are presented in chapters 5 and 6. This chapter provides a summary of the major findings, discusses the two research questions based on the study results, and also addresses the advantages of graphical simulations in teaching complex systems. Pedagogical implications, limitations of this dissertation project, and future research directions are discussed at the end of this chapter.

## Section 1. Summary of Major Findings

### Sequencing Methods

The *EM-AM-Mi* sequencing method produced better recall than the *Mi-AM-EM* and the *AM-Mi-EM* sequencing method. The *EM-AM-Mi* sequencing method grounded abstract system knowledge in concrete examples and also provided a function-oriented conceptual structure (i.e., first learn the system-wide function and then learn how the function is realized) for effective knowledge integration. In this condition, the first learning task was the “aerosol can problem” (the experiential macro level). Participants manipulated the fire icon in the simulation and observed the can exploded. In this task, they experienced the system-wide function of the ideal gas law system. After that, they went on to learn the abstract macro level (i.e., the temperature-pressure relationship when volume is constant). Because this abstract macro level was analogous to and grounded in the aerosol can problem (experiential macro level), participants were more likely to conceptually understand the abstract temperature-pressure relationship.

This *EM-AM-Mi* sequencing method was function-oriented. Participants learned the system-wide function and then probed into the problem around this function. This top-down function-oriented approach helped participants integrate more micro-level concepts. As can be seen, participants in this condition provided more knowledge units in the recall of system knowledge task. However, the item analysis indicated that participants only integrated more micro-level concepts which were explicitly associated with the salient macro-level concept “temperature”, e.g., molecules moving faster when temperature is high, but not the concepts that were directly associated with the abstract

macro-level concept “pressure,” e.g., molecules bump into the walls. The effects of the *EM-AM-Mi* sequencing method was not very robust. This also explains why the effects of this sequencing method were not significant in the comprehension task. In the comprehension task, participants were asked to provide coherent explanations to the questions such as “Why the aerosol can exploded when it is thrown into the fire?” “How do you understand gas pressure?” These questions required participants to externalize micro-level concepts directly associated with both the concrete (i.e., temperature) and abstract macro-level concepts (i.e., pressure).

The effects of the *EM-AM-Mi* sequencing method and level-bridging scaffolding were additive from the perspective of knowledge integration. No interaction was found in the recall of system knowledge task or the comprehension task. However, the effects of the *EM-AM-Mi* sequencing method were not as sustainable as level-bridging scaffolding.

The *Mi-AM-EM* sequencing method produced better transfer performance only when level-bridging scaffolding was given. This result indicates that a sequencing method aligned with the causal structure and explicit scaffolding are both necessary in learning the deep causal structure of a complex system. The *Mi-AM-EM* sequencing method took a “bottom-up” approach, which was aligned with the emergent causal structure of the ideal gas law system, i.e., macro-level phenomena arise from micro-level molecular activity. Participants first learned the behaviors of single molecules, and then expanded to the emergent phenomena of “pressure changes with temperature”. The congruency of the causal processes and the sequencing method helped participants construct a better causal model.

It should be noted that level-bridging scaffolding played a critical role in learning the causal structure. When compared to the other five treatment groups, within the *Mi-AM-EM* & level-bridging treatment group, participants were more likely to recognize the analogy between the source problem (aerosol can problem) and the two new problems (using ice pack to relieve toothache, car tires are more likely to pop in the summer than in the winter). Indicated in the item analysis, a greater proportion of participants in this group provided the concept “increased temperature causes pressure to increase” in their explanation. This indicates that letting students experience the emergent causal process of a complex system (i.e., how an abstract macro level emerges from micro-level dynamics) produces better conceptual understanding. Additionally, although there was a floor effect, a larger percentage of participants in this group provided cross-level causal concepts such as “temperature change causes molecules’ speed change”, “pressure is caused by molecular activity”.

### **Level-Bridging Scaffolding**

Level-bridging scaffolding was found effective in both knowledge integration and understanding of the deep causal structure. Participants received level-bridging scaffolding integrated more micro-level concepts associated with both salient and abstract macro-level concepts, as indicated in the recall of system knowledge task. Additionally, the positive effects sustained in the comprehension task.

Another interesting finding about level-bridging scaffolding: the *EM-AM-Mi* sequencing method produced better recall in general. However, when given level-

bridging scaffolding, participants recalled more important system knowledge, but when no level-bridging scaffolding was given, participants recalled more superficial simulation events (shallow learning). This indicates that level-bridging scaffolding is important for deep learning.

In learning the deep causal structure of the ideal gas law system, merely taking a “bottom-up” approach (*Mi-AM-EM*) to deliver the system knowledge was not sufficient, because the causal structure was implicit, and participants were not likely to actively make connections across system levels. Level-bridging scaffolding made the causal structure explicit, thus participants were able to make the connections across levels and construct better mental models for transfer.

In this study, each learning activity included multiple learning tasks. It took a great deal of effort for participants to make connections within each system level. For example, in order to understand the abstract macro level (temperature-pressure relationship), participants were guided to manipulate the temperature slider in the simulation, conduct multiple observations on the pressure change, record data and make inferences. When learning the micro level (i.e., molecular activity), participants were asked to observe and describe how the single molecules’ behave, interact with each other and interact with the container. As can be seen, it took time and mental effort to understand even a single system level. Without level-bridging scaffolding, participants were likely to treat different learning activities as different problems without making connections. Both the quantitative results in the posttest and qualitative observations indicated that level-bridging scaffolding was necessary for learning the ideal gas law system.

Scaffolding and instructional design are critical in learning complex systems. In this dissertation project, learning tasks in the worksheets played a critical role in students' learning. Participants needed to be sufficiently guided in learning the ideal gas law system.

Further, although it is widely accepted that scaffolding is important, the mechanism of different forms of scaffolding is not clear. This dissertation project was designed around two complementary questions regarding scaffolding in teaching complex systems: 1. How can we chunk and sequence learning activities? And, 2. How can we help students make connections among system levels? This study did not, however, compare “scaffolding” to “no scaffolding.” As can be seen, participants had the same learning activities and the same amount of information, but the same amount of scaffolding information was manipulated differently to study the mechanism of different scaffolding strategies.

In the next two sections, the two research questions will be further discussed based on the study results.

## **Section 2. Chunking and Sequencing Learning Activities in Teaching Complex Systems**

This question centers on how to design proper procedural scaffolding in teaching complex systems. In order to address the “top-down vs. bottom-up” debate, the author reviewed the pedagogical research on complex systems and searched for explanations to

the following question: Why is “top-down” or “bottom-up” sequencing effective or ineffective in teaching a certain type of complex system?

System levels can be analyzed on two different dimensions: 1) macro vs. micro, 2) experiential vs. abstract. In this dissertation, the author focuses on teaching and learning emergent systems. A prototype emergent system structure includes an experiential macro level, an abstract macro level and a micro level. Some general principles for teaching complex systems include grounding abstract system knowledge in concrete examples for knowledge integration; providing organized conceptual structures for knowledge integration; letting students experience the emergent causal processes in a system; and letting students generate abstract macro-level concepts based on analyzing micro-level dynamics.

The first two principles support the *EM-AM-Mi* sequencing method, while the other two support the *Mi-AM-EM* sequencing method. Based on the literature, it is hypothesized that the *EM-AM-Mi* sequencing method facilitates knowledge integration, and the *Mi-AM-EM* sequencing facilitates understanding of the deep causal structure in emergent systems. As a comparison to these two sequencing methods, the *AM-Mi-EM* sequencing method, starting from an abstract macro level, should be less effective than the other two methods in both knowledge integration and understanding of the deep causal structure.

The results of this project support the hypotheses. In learning the ideal gas law system, the *EM-AM-Mi* sequencing method produced better recall of system knowledge (low-level knowledge integration), and the *Mi-AM-EM* sequencing method facilitated constructing a causal model for transfer when level-bridging scaffolding was given. The

*AM-Mi-EM* sequencing method was less effective than the other two, because it did not ground abstract system concepts such as “gas pressure” in experience, nor did it demonstrate the process of how gas molecular activity could cause gas pressure change.

Knowledge integration was measured through recall of system knowledge (e.g., how do molecules behave and interact?), and comprehension (e.g., explain the ideal gas law phenomena learned from the simulation). The *EM-AM-Mi* sequencing method grounded abstract system knowledge in everyday experience. Additionally, the experiential macro-level phenomenon (an aerosol can explodes when temperature increases) was a functional level without much complex dynamics. “How” and “why” questions around system function provide students with a desirable conceptual framework for integrating new information and constructing an explanatory model. As expected, participants in the *EM-AM-Mi* condition recalled more macro-level structural knowledge and micro-level behavior knowledge than those in the other groups. However, this sequencing method may only facilitate integration of salient micro-level behavior knowledge, but not the implicit behavior knowledge that is important for constructing a correct emergent causal model.

Because the causal structure of an emergent system is “bottom-up”, students need to have a mental model representing how the micro-level dynamics give rise to the macro-level phenomena. The two transfer tasks in this study required participants to have a correct causal model of the ideal gas law system and to transfer it to new scenarios. Although the transfer questions and comprehension questions looked similar (both asked participants to explain certain phenomena), they required different knowledge representations. In explaining the problem of “why an aerosol can explodes when thrown



into the fire” (comprehension question), participants were externalizing the content knowledge integrated, and mimicking how the aerosol can problem was explained in the learning process. By contrast, in explaining the problem of “why someone should choose an ice pack to reduce tooth pain,” they had to first understand this phenomenon as an ideal gas law system with multiple levels, and run the mental model (the “bottom-up” causal process) in order to provide correct explanations. The results support the hypothesis that the *Mi-AM-EM* sequencing method facilitates understanding of the deep causal structure, because it allows students to experience the causal processes across system levels.

What do we learn from the findings? Coming back to the framework analyzing the three learning difficulties, the complex nature of a system can be defined on dimensions such as “how difficult it is to integrate and reorganize system knowledge,” “how abstract the macro level or micro level is,” and “how difficult the deep causal structure is.” Whether a sequencing method is effective in teaching a complex system depends on the nature of the system’s complexity. That might explain the contradictory views on sequencing methods in the field of complex systems.

Participants in this study learned the ideal gas law system. The amount of content knowledge of the ideal gas law system is not too overwhelming for seventh-graders. Indeed, students may find everyday ideal gas law phenomena accessible. Temperature-pressure-volume relationships as the abstract macro level are very abstract. The micro-level molecular activity is in general abstract, but is easier to understand than concepts such as “gas pressure.” In this study, the *EM-AM-Mi* sequencing method grounded abstract system knowledge (e.g., pressure and the temperature-pressure relationship) and

facilitated knowledge integration around the system function. The effects of the *EM-AM-Mi* sequencing could be seen most in recall of system knowledge; its effects in comprehension were not significant, but a positive pattern could be seen. One explanation for this is that the amount of system knowledge in this case was not too large, so the effects of the *EM-AM-Mi* sequencing were not very striking. It is expected that this sequencing method could have a larger effect on knowledge integration in learning many biological systems. Ideal gas law is an emergent system and the deep causal structure is the major learning difficulty in comparison to knowledge integration. It is also expected that the *EM-AM-Mi* sequencing method is more effective in teaching non-emergent systems with complex hierarchical structures, e.g., how the management system works in an organization.

The deep causal structure of the ideal gas law system is difficult to understand. The *Mi-AM-EM* sequencing method allows students to experience the emergent causal process; for example, gas molecules move faster or slower depending on the temperature, and gas pressure change emerges from these micro-level dynamics. This sequencing approach matches the correct causal direction, and the congruency may help students construct a correct causal model.

The *Mi-AM-EM* sequencing can potentially help students to construct a full emergent causal model. However, this instructional goal was beyond the scope of this project. Only a few participants mentioned concepts such as “‘all’ molecules cause pressure to go up.” Many participants had misconceptions in this area; for example, quite a few mentioned, “molecules want to move around and bump into the walls” (intentionality of elements). Misconceptions in learning emergent systems are robust

(Chi, 2005), and it takes time and effort to facilitate conceptual changes. In this study, given that participants only learned the topic for two class periods, and that there was no explicit instruction on emergent concepts, the author did not expect dramatic conceptual changes. The focus was on mastering content knowledge and constructing a basic causal model of the system. In future research, the goal of constructing a correct emergent causal model needs to be addressed and properly measured.

Since students go through stages of conceptual changes in learning emergent systems, constructing a basic causal model (understanding that it is the micro-level dynamics that cause the macro-level phenomena) may prepare students for future learning. This is an interesting assumption that deserves future research. It would also be interesting to see whether students go through a similar trajectory in constructing an emergent causal model.

It is reasonable to claim that the *EM-AM-Mi* and *Mi-AM-EM* sequencing methods may lead to functionally different knowledge representations. The *EM-AM-Mi* sequencing method guides students in integrating detailed system information around the system-wide function. Thus, when asked “how” and “why” questions around the function, students are more likely to externalize system structural and behavior information, because both the learning process and the measurement probe into the system in a “top-down” manner.

With the *Mi-AM-EM* sequencing method, students are guided to analyze the system from a micro level and to experience the process by which micro-level dynamics lead to macro-level phenomena. This may help them to construct a mental simulation correctly representing the causal process of an emergent system. In a new context,

students are more likely to have a “runnable” mental model of the system, and to transfer it.

Listed above are some explanations for the interaction between the sequencing methods and the measurement tasks. Further research, though, is needed to clarify many issues, such as, “How to define and measure students’ knowledge representations of a complex system?” Only one chemical system was studied in this project, and it is not clear whether or not similar results could be found in learning other types of complex systems. Further, the congruency of “the process of constructing a mental model” and the “the process running this mental model” seems to be the core factor explaining the findings. This is another interesting research topic.

One important implication for instruction is that one sequencing method does not achieve all instructional goals. Although this dissertation project compares different sequencing methods, the author does not argue that one sequencing method should be used more than the other. From the perspective of instructional designers and teachers, complex systems need to be analyzed on different dimensions. In the long run, varied sequencing methods can be used to help students construct more flexible mental models. This is another interesting future research direction.

### **Section 3. Level-Bridging Scaffolding**

Many studies have demonstrated the importance of inter-level experience in learning complex systems (e.g., Levy & Wilensky, 2008). Students may lack the cognitive and metacognitive ability to actively make connections, making scaffolding

critical. Based on many scaffolding theories, we need to design tasks that encourage active connection making and self-explanation. The findings of this project provide evidence for the above claim. The effects of level-bridging scaffolding were significant both in knowledge integration and understanding of the deep causal structure in learning the ideal gas law system.

In this project, two forms of level-bridging scaffolding were applied: 1) dynamically linking two simulations, which is a kind of software-realized scaffolding, and 2) inter-level questions that explicitly ask students to explain how one level of the system explains the dynamics of another level.

Based on some qualitative observation during the data collection process, the author has reason to believe that these two forms of scaffolding complement each other. Inter-level questions initiate level-bridging activities, and dynamically linked simulations provide resources and data during this process. In learning the ideal gas law system, participants would start to compare two system levels and have more effective self-explanations after reading the inter-level questions. In the final learning activity, when participants were asked to connect the experiential macro level, the abstract macro level, and the micro level, if the two simulations run simultaneously, participants had more “aha” and “I see” moments.

Level-bridging scaffolding facilitate knowledge integration regardless of sequencing method. Explicitly asking students to make connections among system levels is a good scaffolding strategy. Without level-bridging scaffolding, however, students tend to integrate fragmented system knowledge. As can be seen, in this study, the effects of

level-bridging scaffolding were significant in both recall and comprehension of system knowledge.

In the transfer task, the *Mi-AM-EM* sequencing was effective only when level-bridging scaffolding was given. This demonstrates the importance of inter-level experience in understanding the deep causal structure of a complex system. Simply delivering the system knowledge sequentially following the causal direction is insufficient in helping students to construct causal models. Qualitative observation in this study also supports this assumption; participants in the no level-bridging scaffolding condition tended to treat the aerosol can presentation and the gas container presentation as two separate problems, and did not actively make connections.

The author would like to emphasize the importance of level-bridging scaffolding in learning complex systems. Level-bridging scaffolding encourages students to make connections through active self-explanations, which are the essential processes for deep learning. Level-bridging scaffolding is critical for cross-level reasoning, and it can be in various forms. This has implications for everyday instruction. For example, to help students understand how “current” and “voltage” emerge from micro-level electrons’ behaviors, the teacher must explicitly ask inter-level questions for reflection and self-explanation. Level-bridging scaffolding may be a generalizable instructional strategy in tackling complex math and science topics. Future research is needed to support this claim.

One limitation of this study is that the effects of the two forms of level-bridging scaffolding (i.e., inter-level questions and dynamic link of simulations) cannot be teased apart by any quantitative method. Future research is needed to clarify the effects of each

form. Based on previous pilot studies, the author has reason to believe that dynamic link of multiple representations can be effective only when students understand each individual representation. In one earlier pilot study conducted with a sample of adult students and an early version of the ideal gas law simulations, it is found that dynamically linking two representations at the beginning of a lesson actually produces worse performance when compared to learning one representation at a time (Li, Black & Gao, 2012). Dynamic link of multiple representations, in other words, could cause cognitive overload if students are not familiar with any single representations. From a research perspective, further studies are needed to look at the functions and restrictions of various forms of level-bridging scaffolding. From the perspective of everyday instruction, mixed forms of scaffolding can be applied.

#### **Section 4. Graphical Simulations as Effective Learning Tools**

Although this study did not quantitatively test the effects of the simulation-based environment, observing the learning process in this study did provide some insights into their benefits. Graphical simulations have many advantages for teaching complex systems. This project utilized a simulation-based environment in teaching the ideal gas law system. Simulations are able to demonstrate the otherwise implicit and abstract system dynamics. In this project, two simulations visualizing different levels of ideal gas law phenomena were used (see chapter 4). The aerosol can simulation represents an experiential macro level of the system, and it is intuitive and motivating. The gas container simulation enables students to observe and analyze the micro-level gas

molecular activities, manipulate variables, and observe the system dynamics and processes. The interactive and dynamic nature of the simulations facilitates inference making. Most of the study participants were able to work on the worksheets questions independently with the help of the simulations.

Multiple representations enable students to analyze the ideal gas law system from multiple perspectives, and to construct a “levels” lens. In this simulation-based environment, students are able to analyze an experiential ideal gas phenomenon (the aerosol can explodes when the temperature is high), the abstract macro-level factors (the temperature-pressure relationship when volume is constant), and the micro-level molecular activities. Techniques such as “dynamic link” of multiple representations can potentially facilitate level bridging. In this environment, the aerosol can and gas container simulations could be linked and run simultaneously. Multiple representations being delivered and learned sequentially, and then being dynamically linked for level bridging, is a form of software-realized scaffolding, which is aligned with the two complementary external scaffolding strategies: sequencing the tasks, and then level-bridging scaffolding. Although this dissertation focuses on scaffolding, it also provides insights into how to design better learning environments. How to embed more software-realized scaffolding into learning environments is also a promising research direction.

## **Section 5. A Multi-Dimensional Framework Analyzing Learning Difficulties**

Different learning difficulties may define the complexity level more than others in learning a certain complex system. We need a multi-dimensional framework, therefore, to



analyze complex systems for instructional purposes. This dissertation study attempted to utilize such a multi-dimensional framework to develop hypotheses and explain findings. In this dissertation project, difficulties in learning complex systems were also analyzed on three particular aspects: Knowledge integration, learning the deep causal structure and dealing with abstract system levels. The results of this study did demonstrate that different sequencing methods impact different aspects of learning. The *EM-AM-Mi* sequencing method had positive effects on knowledge integration and the *Mi-AM-EM* sequencing method was important for learning the deep causal structure of the ideal gas law system.

The author is open to criticism regarding this framework. The topic taught in this study is a chemical complex system, which may not be representative of the whole complex systems field. Future research is needed to improve and validate this multi-dimensional framework. Such a framework can potentially explain contradictory findings, and inform instructional design.

## **Section 6. Pedagogical and Instructional Implications**

The *EM-AM-Mi* sequencing method takes a “top-down” approach and is function-oriented. This sequencing method supports knowledge integration. In learning systems with many levels and ascending complexity from a macro to a micro level (e.g., human circulatory systems), the *EM-AM-Mi* sequencing method can be more effective. Effective knowledge integration is the primary hurdle in those contexts. It’s difficult for novice learners to connect fragmented system knowledge and provide coherent explanations. For

example, in teaching the human respiratory system, it is more effective to start from the experiential macro-level function “breathing”. Around this function, students can be guided to learn how the organs and their substructures work together to realize this system-wide function. A “top-down” function-oriented approach helps students to integrate system structural and behavior knowledge at lower levels. The *EM-AM-Mi* sequencing method may be particularly effective in teaching non-emergent hierarchical systems (e.g., how an organization functions, how a machine with hierarchical structure works), because these systems often have many levels with ascending difficulty from a higher level to a lower level. These systems do not have counter-intuitive emergent causal structures and the major learning difficult is knowledge integration.

The *Mi-AM-EM* sequencing method is effective in teaching emergent systems. It allows students to experience how a macro-level phenomenon emerges from micro-level dynamics. The congruency of the sequencing method and the emergent process may help students construct better mental models for transfer. In teaching many chemical systems and physics systems involving emergence, this sequencing method is more effective. For example, in teaching the ideal gas law system, the teacher can let students analyze the behaviors of a single molecule and then gradually expand to the emergent process. In teaching abstract concepts such as “voltage”, the teacher can let students analyze single electrons’ behaviors and observe how voltage arises as an emergent function. The *Mi-AM-EM* sequencing method facilitates understanding of the deep causal structure thus enhances transfer.

This study also shows that no sequencing method meets all ends. Different sequencing method may be used at different learning stages. For example, when students

first learn the respiratory system, the teacher can start from the experiential macro level to help students integrate detailed system knowledge. After students have constructed a good explanatory model, a “bottom-up” approach starting from the molecular-level mechanism (e.g., chemical reactions, O<sub>2</sub> and CO<sub>2</sub> molecules movement) may help students understand the implicit emergent processes involved. When teaching the magnetic field system, the teacher can first use the *EM-AM-Mi* sequencing method. Because both the abstract macro level (i.e., a formal representation of a magnetic field) and the micro level (magnets’ behaviors) are very abstract, they need to be grounded in everyday experience. After students have grasped the abstract system levels, the *Mi-AM-EM* sequencing method can be utilized to teach the emergent causal structure and help students transfer the knowledge.

Level-bridging scaffolding has sustainable effects on deep learning. Level-bridging scaffolding is an effective strategy in teaching complex systems, and it can be implemented widely in everyday science classrooms. Level-bridging scaffolding can be in different forms either enable or enhance cross-level connection making. For example, when teaching genetics concepts, inter-level questions can be very effective, e.g., “Use the knowledge of DNA, and explain why the proteins have different functions.” “Use the knowledge of protein, and explain why the organs have different features and functions.” Another example, in teaching the electrical system, we can explicitly ask inter-level questions such as “How do single electrons behave? How does voltage arise from electrons’ behaviors?” At the same time, simulations that demonstrate the process of voltage emerging can be used as an effective learning tool. Explicit inter-level questions may initiate cross-level reasoning, and multiple representations dynamically linked can

facilitate active connection making. At the classroom level, various level-bridging scaffolding strategies can be used for the same purpose.

### **Section 7. Limitations of this Dissertation Project**

There are limitations to the methodology of this dissertation project. First, the “gas container” simulation represents two levels of the ideal gas law system: the abstract macro level (the temperature-pressure-volume relationships) and the micro level (gas molecular activity). The sequencing methods were manipulated by changing the order of the learning activities in the booklet; i.e., participants would focus on either the abstract macro level or the micro level at a certain stage based on the questions. However, there could be some noise in this manipulation.

Second, it is difficult to separate the effects of the dynamic link of representations and the inter-level questions as two forms of level-bridging scaffolding. Follow-up studies are needed to examine different forms of level-bridging scaffolding.

Third, the validity and reliability of the measures are open to criticism. Only open-ended questions were used to measure knowledge integration and understanding of the deep causal structure. Not all of the items in the coding scheme showed the same pattern and some items had a floor effect. Future research is needed to study how to better measure performance in learning complex systems.

## Section 8. Future Research Directions

The author argues for a multi-dimensional framework in analyzing difficulties in learning complex systems. In this project, three learning difficulties are summarized: knowledge integration, understanding of the deep causal structure and dealing with the abstract system levels. This framework has not been validated, and the author is open to criticism. Future pedagogical research on complex systems is needed to improve this framework. Scaffolding research on complex systems from different disciplines is also needed in order to develop a more generalizable framework.

Different sequencing methods are compared in this dissertation, and the purpose is to analyze their mechanism; i.e., why a sequencing method is effective or ineffective on a certain aspect. In everyday instruction, the *EM-AM-Mi* and *Mi-AM-EM* sequencing methods may be used at different learning stages. It is interesting to study whether mixed methods could lead to more flexible mental models in the long run.

This study demonstrates that level-bridging scaffolding is an effective strategy in teaching complex systems. It supports self-explanation and connection making. This strategy may be generalized to other science and math learning areas, thus deserves further research. One limitation of this study is that the effects of two forms of level-bridging scaffolding cannot be teased apart. Future studies are needed to clarify this.

The effects of explicit instruction of “emergence” concept remain unclear. In this study, students in the *Mi-AM-EM* & level-bridging scaffolding group were better able to understand the basic causal structure of the system (i.e., gas molecular activity causes the gas pressure change, which explains the phenomena), but explanations about “emergence” (i.e., “all” molecules move randomly, they behave simultaneously

following same rules, and pressure arises from the micro-level dynamics) were very rare. How to help students fully grasp an emergent model needs further study. It's important to study the learning trajectory and conceptual changes students go through in learning complex systems.

This study tests two types of external scaffolding. It would be interesting to study how to embed these scaffolding methods in a simulation-based environment; for example, with the inter-level questions being delivered as prompts.

Finally, aligned with a multi-dimensional framework in analyzing complex systems, we need more valid and reliable measures. Specifically, we need to develop better measures that capture students' knowledge representations of complex systems. More research is needed in this direction. How to effectively measure students' performance in learning complex systems is an important question. In this dissertation project, the author measured student learning with open-ended questions. The author made this decision because these are a more direct measure of students' knowledge representations when compared to multiple-choice questions. This assumption is simply based on previous pilot studies and lack of empirical evidence. In sum, the measures in this dissertation study have many limitations. More discussions and studies of how to measure complex systems learning are needed for both pedagogical and research purposes.

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## Appendix A. Sample Questions in the Worksheets

A question about the experiential macro level:

**Explore:** This is an aerosol can filled with gas



1. Slowly drag the fire holder to the bottom of the aerosol can, observe and describe what happens?

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Sample questions on the abstract macro level:

1. **Don't move anything, hypothesize:** as temperature rises, how will the pressure change?

---

**Now please move the Temperature slider, and record the data like a scientist!**

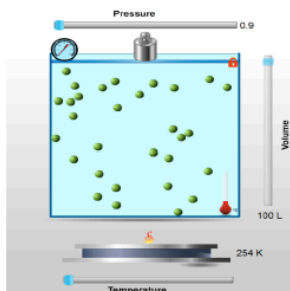
2. **Collect data:**

Slowly drag the **temperature slider** from left to right, record the values of "temperature", "pressure" and "volume" for 5 times.

Temperature	Pressure	Volume

## Appendix A. Sample Questions in the Worksheets (Continued)

Sample questions on the micro-level dynamics:



**Please look at one molecule. Does it move in a certain direction or in random directions?**

---

**How could a molecule keep changing directions? How do molecules interact with each other?**

---



---

**Compare different molecules, which of the following statement is correct?**

- A. All molecules move and interact at the same time in more or less the same way
- B. All molecules move and interact in very different ways

**How do gas molecules interact with the walls of the container ?**

---

**Please drag the **temperature slider** back and forth, describe how do the gas molecules behave and interact with each other? Take notes:**

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## Appendix A. Sample Questions in the Worksheets (Continued)

Please estimate how many times each wall is hit by molecules per second?

Temperature	Speed of all molecules	How many times each wall is hit by molecules per second ( <b>please just estimate</b> )
250K	Very slow	
300K	Slow	
400K	Medium	
450K	Fast	

## Appendix B. Item Analysis: Recall of System Knowledge

Items with \* may support the hypotheses

Items with X may be against the hypotheses

Recall of System Knowledge (Percentage of Participants Getting Each Item Correct)									
<i>EM-AM-Mi</i> vs. Other		Item 1: Gas is composed of molecules <i>(Micro-Level Structural Knowledge)</i>	X Item 2: Gas molecules move randomly <i>(Micro-Level Behavior Knowledge)</i>	*Item 3: Mention speed of molecules <i>(Micro-Level Behavior Knowledge)</i>	Item 4: Mention the relationship between temperature and speed of molecules <i>(Micro-Level Behavior Knowledge)</i>	*Item 5: Molecules bump into each other <i>(Micro-Level Behavior Knowledge)</i>	X Item 6: Molecules bump into the walls <i>(Micro-Level Behavior Knowledge)</i>	*Item 7: Correctly label Temperature, Pressure, Volume <i>(Macro-Level Structural Knowledge)</i>	*Item 8: Correctly label unit names for Temperature, Pressure and Volume <i>(Macro-Level Structural Knowledge)</i>
<i>EM-AM-Mi</i>	Percentage	.7000	.50	.40	.13	.80	.08	.70	.40
Other	Percentage	.6747	.59	.29	.10	.66	.18	.60	.24
Total	Percentage	.6829	.56	.33	.11	.71	.15	.63	.29

## Appendix B. Item Analysis: Recall of System Knowledge (Continued)

Recall of System Knowledge (Percentage of Participants Getting Each Item Correct)									
Level Bridging		X Item 1: Gas is composed of molecules <i>(Micro-Level Structural Knowledge)</i>	Item 2: Gas molecules move randomly <i>(Micro-Level Behavior Knowledge)</i>	*Item 3: Mention speed of molecules <i>(Micro-Level Behavior Knowledge)</i>	*Item 4: Mention the relationship between temperature and speed of molecules <i>(Micro-Level Behavior knowledge)</i>	*Item 5: Molecules bump into each other <i>(Micro-Level Behavior knowledge)</i>	Item 6: Molecules bump into the walls <i>(Micro-Level Behavior Knowledge)</i>	*Item 7: Correctly label Temperature, Pressure, Volume <i>(Macro-Level Structural Knowledge)</i>	*Item 8: Correctly label unit names for Temperature, Pressure and Volume <i>(Macro-Level Structural Knowledge)</i>
Level Bridging	Percentage	.6230	.57	.41	.15	.75	.15	.77	.36
No Level Bridging	Percentage	.7419	.55	.24	.06	.66	.15	.50	.23
Total	Percentage	.6829	.56	.33	.11	.71	.15	.63	.29

### Appendix C. Item Analysis: Comprehension

Comprehension (Percentage of Participants Getting Each Item Correct)						
Level Bridging		Item 1: Mention increased temperature <i>(Macro-Level Concrete Concept)</i>	*Item 2: Mention increased pressure <i>(Abstract Macro-Level Concept)</i>	*Item 3: Increased temperature causes pressure to increase <i>(Macro-Level Abstract Rule)</i>	*Item 4: Increased temperature causes molecules to move faster <i>(Micro-Level Behavior Knowledge)</i>	Item 5: Molecular activity causes pressure to go up <i>( Cross-Level Abstract Causal Relation )</i>
Level Bridging	Percentage	.5738	.3279	.1639	.2787	.0656
No Level Bridging	Percentage	.5161	.2581	.0323	.1855	.0323
Total	Percentage	.5447	.2927	.0976	.2317	.0488

### Appendix C. Item Analysis: Comprehension (Continued)

Comprehension Cont. (Percentage of Participants Getting Each Item Correct)					
Level Bridging		Item 6. Mention pressure as the cause of a concrete gas law phenomenon (Abstract Macro-Level Concept)	Item 7. Mention correct causal relationship between temperature and pressure (Abstract Macro-Level Rule)	*Item 8. Molecules moving faster causes pressure to go up (Abstract Cross-Level Causal Relation)	Item 9. Molecules bumping more causes pressure to go up (Abstract Cross-Level Causal Relation)
Level Bridging	Percentage	.0656	.1557	.2295	.0000
No Level Bridging	Percentage	.0161	.1935	.1613	.0484
Total	Percentage	.0407	.1748	.1951	.0244

Comprehension Cont. (Percentage of Participants Getting Each Item Correct)							
Level Bridging		Item 10. Higher temperature, higher pressure (Abstract Macro-Level Rule)	*Item 11. Molecules move faster (Micro-level behavior knowledge)	Item 12. Molecules bump more (Micro-Level Behavior Knowledge)	Item 13. To decrease pressure, one needs to reduce temperature (Abstract Macro-Level Rule)	*Item 14. Molecules move slower (Micro-Level Behavior Knowledge)	Item 15. Molecules bump less (Micro-Level Behavior Knowledge)
Level-Bridging	Percentage	.6721	.1885	.0164	.6066	.1885	.0000
No Level-Bridging	Percentage	.7419	.0565	.0161	.6452	.0887	.0000
Total	Percentage	.7073	.1220	.0163	.6260	.1382	.0000

### Appendix D. Item Analysis: Transfer

Transfer (Percentage of Participants Getting Each Item Correct)											
Condition		*Ice pack reduces temperature	*Reduced pressure in the tooth leads to less pain	*Reduced temperature causes pressure to decrease	Reduced temperature causes molecules to move slower	Mention gas molecules in the toothache problem	Temperature higher in summer than in winter	*Increase pressure as the direct cause in the car tire problem	Higher temperature causes pressure to increase	*Increased temperature causes speed of molecules to increase	*Pressure emerges from molecular activity
<i>Mi-AM-EM &amp; Level-Bridging</i>	Percentage	.6579	.0789	.3158	.0526	.0789	.4211	.2368	.1579	.2632	.1579
<i>Mi-AM-EM &amp; No Level-Bridging</i>	Percentage	.4783	.0217	.0000	.1304	.0435	.3696	.1522	.2174	.0870	.0217
Other & Level-Bridging	Percentage	.5595	.0119	.0476	.0238	.0357	.3810	.1190	.1429	.1429	.0238
Other & No Level-Bridging	Percentage	.4359	.0000	.0256	.0513	.0128	.3846	.1538	.1795	.1795	.0513
Total	Mean	.5203	.0203	.0732	.0569	.0366	.3862	.1545	.1707	.1626	.0528



### Appendix E. Correlation Matrix of Three Posttest Tasks

Correlations				
		Recall of System Knowledge	Comprehension	Recall of Simulation Events
Recall of System Knowledge	Pearson Correlation	1	.319**	.151
	Sig. (2-tailed)		.000	.096
	N	123	123	123
Comprehension	Pearson Correlation	.319**	1	.148
	Sig. (2-tailed)	.000		.101
	N	123	123	123
Recall of Simulation Events	Pearson Correlation	.151	.148	1
	Sig. (2-tailed)	.096	.101	
	N	123	123	123
**. Correlation is significant at the 0.01 level (2-tailed).				

#### Notes:

1. The recall of system knowledge task (low-level knowledge integration) and the comprehension (high-level knowledge integration) task are significantly correlated.
2. The recall of simulation events task (shallow learning) is not correlated with the recall of system knowledge and comprehension tasks

## Appendix F. Example Answers (Transfer Task)

**Question 1. An infected tooth forms a tiny space that fills with gas. The gas puts pressure on the nerve of the tooth, causing a toothache. Which of the following the patient should choose to relieve the pain: A. Moist heat B. Ice pack**

**Why? Explain:**

**Question 2. Car tires overinflated are more likely to pop in the summer than in the winter, please explain why that happens?**

- **Answers that indicate participants didn't recognize the analogy between the aerosol can problem and the new problem:**

Answer 1 (Question 1):

*I will choose ice pack, because the heat will do nothing but the ice will make the pain go away.*

Answer 2 (Question 1):

*The coldness of the ice relaxes the pain way.*

Answer 3 (Question 2):

*The rubber of the wheel begins to become thin making it pop.*

Answer 4 (Question 2):

*Because in the summer the heat takes up gas and it will make it pop.*

- **Answers that indicate participants transferred some causal knowledge but didn't grasp a good causal model of the system:**

Answer 1 (Question 1):

*Should use an ice pack because it will slow down the molecules and pain.*

## Appendix F. Example Answers (Continued)

### Answer 2 (Question 1):

*I think that is because the heat from the sun hit the floors that cars drive on, and the heat causes the pressure to increase.*

### Answer 3 (Question 2)

*Because if you choose moist heat, the molecules will go crazy causing a toothache  
I choose ice pack because the heat will go away, the cold will stop the pressure from going high.*

### Answer 4 (Question 2)

*Because when the temperature is hot molecules move faster so it hurts more. If the temperature is cold, it lowers the pressure, and makes your tooth not hurt as much.*

- **Answers that indicate participants transferred both intra-level and cross-level causal knowledge:**

### Answer 1 (Question 2):

*Because the molecules in the tire start to speed up in the heat and the pressure rises making it pop.*

### Answer 2 (Question 2):

*In the summer it's hot. Molecules move around faster, and it creates pressure in the tire.  
The hotter the temperature is, the more pressure, causing the tire to pop.*